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Title:	Stabilization Program Betatron Course
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Stabilization Program Betatron Course

STABILIZATION PROGRAM
NNSA NA-42

Betatron Course

Lesson 1

Course Overview and Betatron vs. Golden XRS-3

Course Schedule

	Monday Aug. 17	Tuesday Aug. 18	Wednesday Aug. 19	Thursday Aug. 20	Friday Aug. 21
0700	Radiological Work Permit (RWP) Briefing - INL	Lesson 4: X-ray Energy, Contrast, Collimation & Filtering	Lesson 6: Radiography Setup	Practical #2	Practical #4
0730	Lesson 1: Course Intro & Betatron vs. XRS-3		Lesson 7: Betatron Troubleshooting & Maintenance		
0800	Lesson 2: Rad Interaction, Detection & Safety	XRS-3 vs. Betatron X-raying Various Materials	Magnification Effects		
0830					
0900	Lesson 3: Betatron Operation and Safety				
0930	Betatron Operation and Radiation Characterization				
1000					
1030					
1100					
1200	LUNCH	LUNCH	LUNCH	LUNCH	LUNCH
1300	Rad Worker II (@ NRGROC) John Giles, INL	Lesson 5: Signal and Noise	Practical #1	Practical #3	Practical #4 cont'd
1330		X-raying Test Plates			
1400					
1430					
1500					
1530					
1600	Adjourn	Adjourn	Adjourn	Adjourn	Adjourn

Course Goals

- **Operate the Betatron** SAFELY and with proficiency
- Have a basic understanding of how to **take a quality radiography using a high energy x-ray generator**

Top 10 Things to Take Away

Number 1

Safe Betatron operation

Top 10 Things to Take Away

Number 2

Image Quality is a function of

- Contrast
- Resolution
- Noise

What is a Contrast-Detail-Dose Curve?

Top 10 Things to Take Away

Number 3

What is Contrast and what affects it?

Top 10 Things to Take Away

Number 4

What is “high energy” radiography and how is it different from ‘low energy?”

Top 10 Things to Take Away

Number 5

What is noise in radiography and why is it important?

Top 10 Things to Take Away

Number 6

How can we compensate for a lack of resolution?

Top 10 Things to Take Away

Number 7

Why is scattered radiation a bad thing?

Top 10 Things to Take Away

Number 8

What do we need to know about the Betatron?

Top 10 Things to Take Away

Number 9

What do we need to know about the Scanner?

Top 10 Things to Take Away

Number 10

What is Resolution and what affects it?

XRS-3 vs. Betatron

- **Golden XRS-3 Specs**
  - **Energy?**
    - ___
    - Average energy ___
  - **Dose Rate?**
    - ___ µSv/pulse at 1 meter
  - **HVL?**
    - ___ mm steel
  - **Max penetration?**
    - ___ mm steel

XRS-3 vs. Betatron

- **Golden XRS-3 Specs**
  - **Energy**
    - 270 kVp
    - Average energy ~100 keV
  - **Dose Rate?**
    - ___ µSv/pulse at 1 meter
  - **HVL?**
    - ___ mm steel
  - **Max penetration?**
    - ___ mm steel

XRS-3 vs. Betatron

- **Golden XRS-3 Specs**
  - **Energy?**
    - 270 kVp
    - Average energy ~100 keV
  - **Dose Rate**
    - 4.5 µSv/pulse at 1 meter
    - 13.4 mSv/hour (3000 pulses)
  - **HVL?**
    - ___ mm steel
  - **Max penetration?**
    - ___ mm steel

XRS-3 vs. Betatron

- **Golden XRS-3 Specs**
  - **Energy?**
    - 270 kVp
    - Average energy ~100 keV
  - **Dose Rate?**
    - 4.5 µSv/pulse at 1 meter
    - 13.4 mSv/hour (3000 pulses)
  - **HVL**
    - 8 mm steel
  - **Max penetration?**
    - ___ mm steel

XRS-3 vs. Betatron

- **Golden XRS-3 Specs**
  - **Energy**
    - 270 kVp
    - Average energy ~100 keV
  - **Dose Rate**
    - 4.5 µSv/pulse at 1 meter
    - 13.4 mSv/hour (3000 pulses)
  - **HVL**
    - 8 mm steel
  - **Max penetration**
    - ~25 mm steel

XRS-3 vs. Betatron

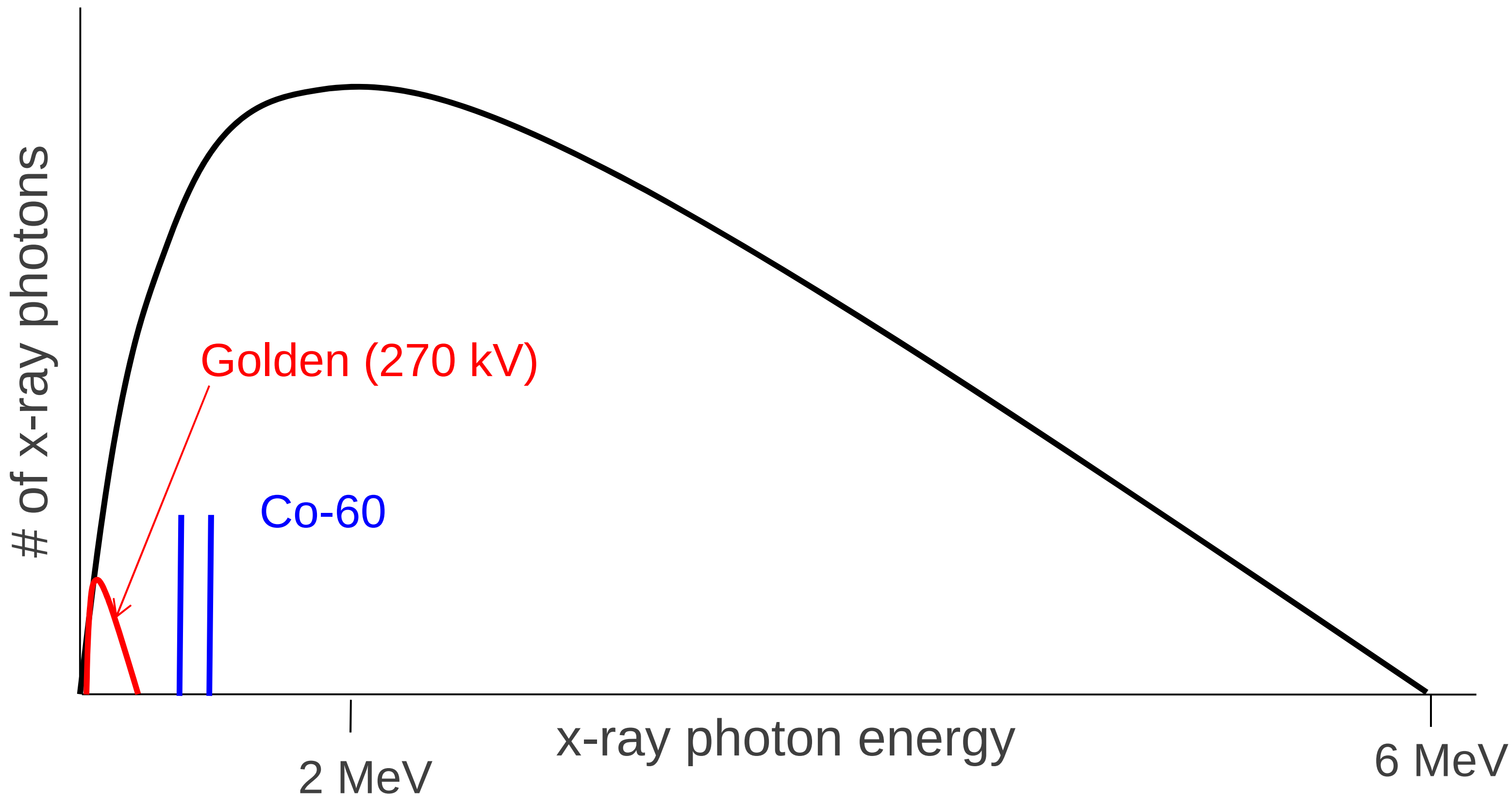
- **Golden XRS-3 Specs**
  - **Energy**
    - 270 kVp
    - Average energy ~100 keV
  - **Dose Rate**
    - 4.5 µSv/pulse at 1 meter
    - 13.4 mSv/hour (3000 pulses)
  - **HVL**
    - 8 mm steel
  - **Max penetration**
    - ~25 mm steel

- **Betatron Specs**
  - **Energy**
    - Adjustable 2 to 6 MeV (2000 to 6000 keV)
  - **Dose Rate**
    - Up to 80 mSv/minute
  - **HVL**
    - 2 MeV 20 mm steel
    - 4 MeV 23 mm
    - 6 MeV 28 mm
  - **Max penetration**
    - ~ 200 mm steel

	Golden XRS-3	Betatron PXB-6MJ
Dose/Pulse	0.45 mR/pulse @1 m **4.5 µSv/pulse @1 m**	0.67 mR/pulse@1 m **6.7 µSv/pulse @1 m**
Dose Rate	15 pulses per second 6.8 mR/sec @ 1 m **68 µSv/sec @ 1 m**	200 pulses per sec 133 mR/sec @ 1 m **1.33 µSv/sec @ 1 m**
Maximum Output	Up to 99 pulses per exposure 44.6 mR @1 m **0.446 µSv @1 m**	8 R/min @1 m **80 mSv/min @1 m** **4.8 Sv/hr @1 m**
At Maximum Output		
High Radiation Area (100 mR/hr) **(1 mSv/hr)**	3.7 m (12.2 ft)	69.3 m (277 ft)
Radiation Area (5 mR/hr) **(50 µSv/hr)**	16.4 m (54 ft)	310 m (1020 ft)
Controlled Area (2 mR/hr) **(20 µSv/hr)**	26 m (85.5 ft)	490 m (1610 ft)
Controlled Area **(25µSv/hr)**	23.2 m (76 ft)	440 m (1445 ft)

X-ray Spectrum

- **Bremsstrahlung Spectrum (6 MeV)**



STABILIZATION PROGRAM NNSA NA-42

Betatron Course

Lesson 2

Radiation Interactions, Detection, and Safety

Lesson Objectives

- Explain **how radiation interacts** with material
- Identify the effects **scatter** has on an x-ray image
- Define **attenuation**
- Explain the **Betatron's effect on attenuation** of various material **vs. the Golden XRS-3**
- Identify the **occupational dose limits** and **radiation control boundaries** for the U.S. and Australia

The Goal of Radiography?

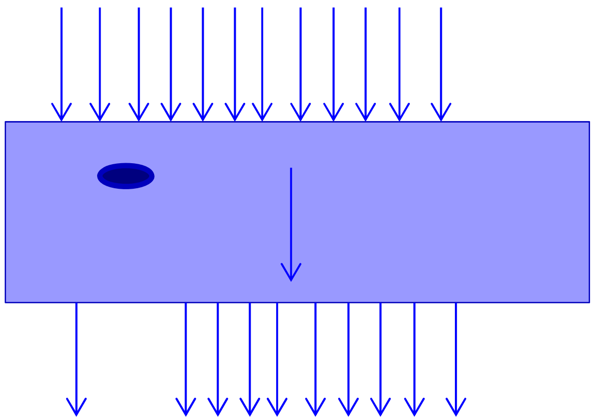
- Produce an *interpretable* image (may not be the prettiest image)
- The image is then *interpreted* against a set of known features
- Radiographers and interpreters must be well versed in *both* the physics *and* the art of radiography-- radiography is not an exact science

The Art of Radiography

- Determining edges in blurry images
- Collapsing 3D parts on to a 2D image
- Relative attenuation of features based on thickness, density, and atomic number
- Taking into account scatter, film/detector response, alignment/parallax
- Practice, Practice, Practice
- Now to the science ….

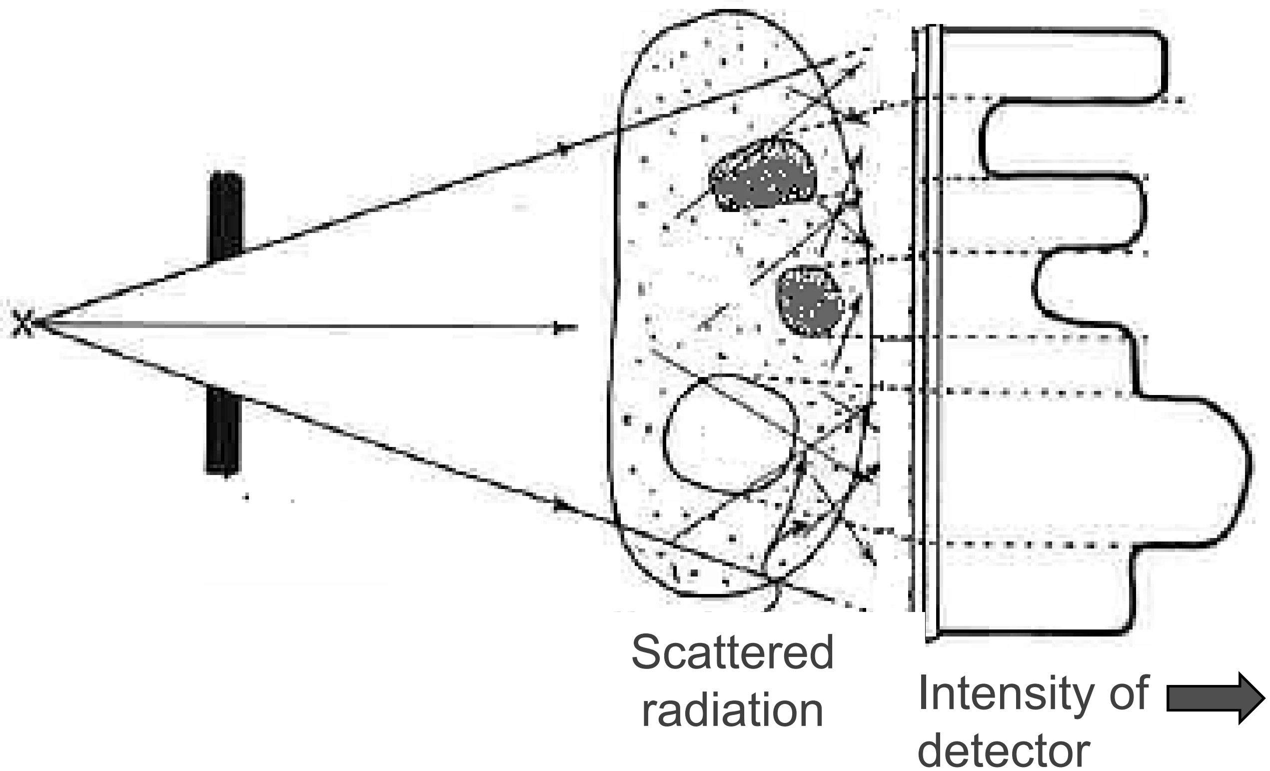
Radiation Interactions, Detection and Safety

- **Main Idea**
  - How does radiation interact with matter?



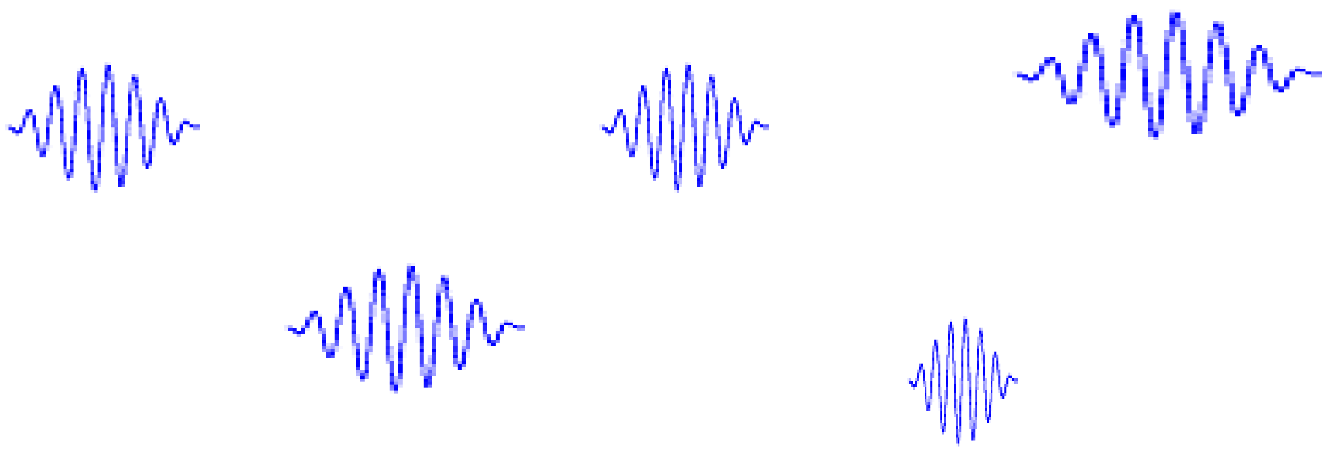
  - Radiography: detect changes in radiation pattern passing through an object

Radiography:
Radiation Pattern through an Object



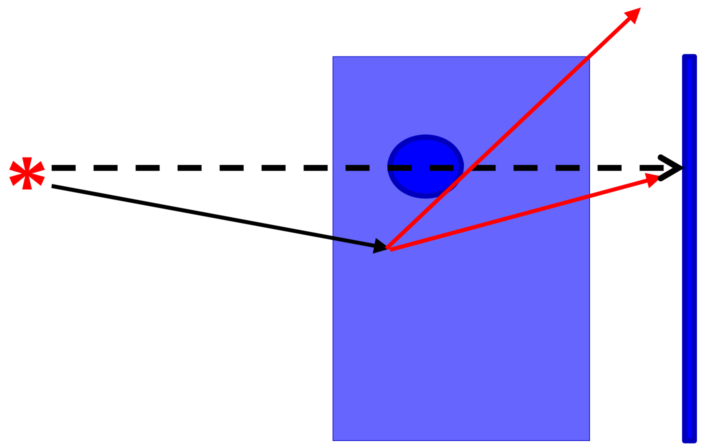
Photons

- X-rays are Photons
- Photons are discrete “packets” of energy
- Dual particle/wave characteristics



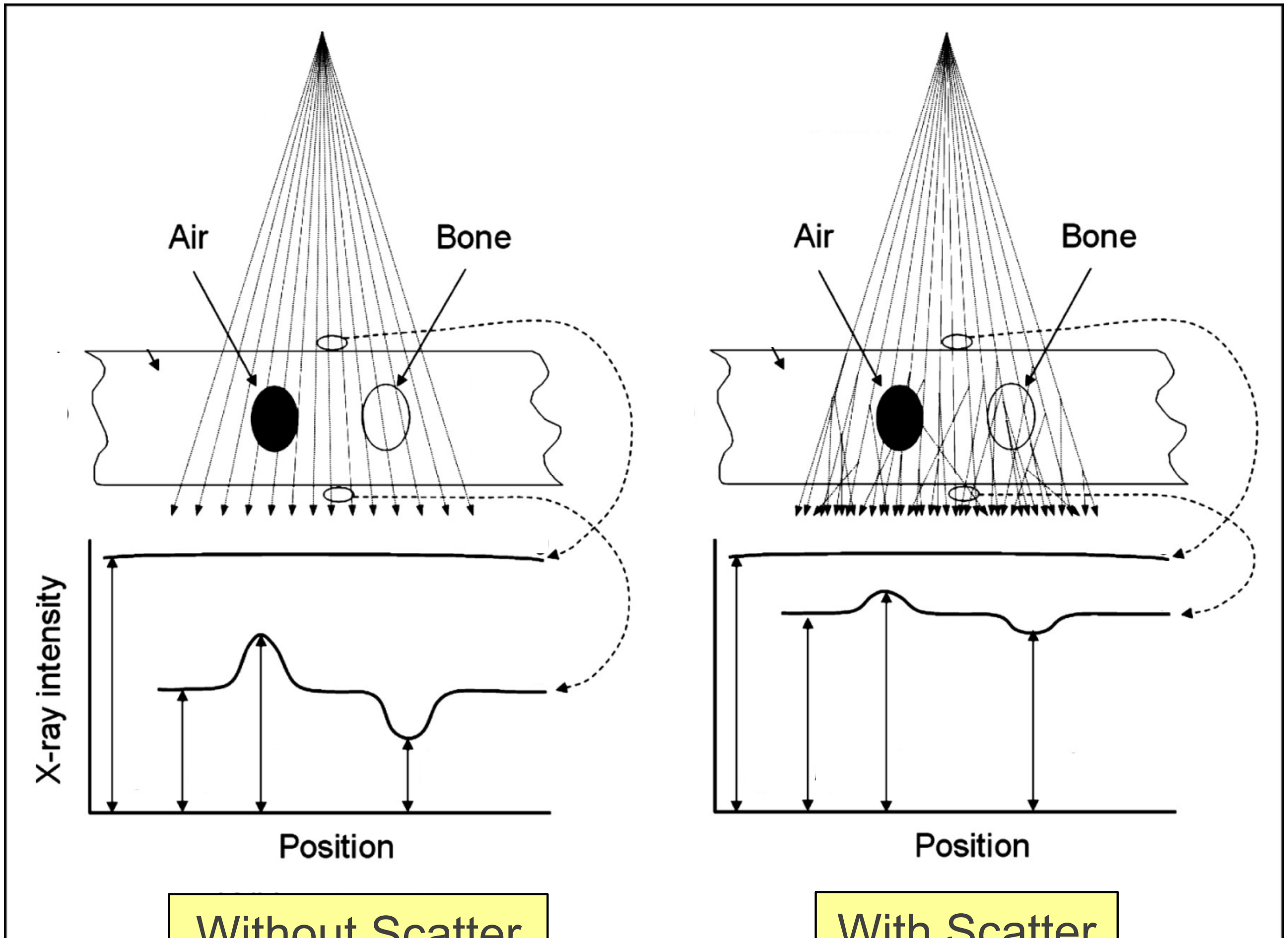
Scatter Problem

- Scatter, if detected in image, is bad
- Does not add any information
  - Instead, detracts from information



Scattered photon appears to have come from a different place

Scatter Degrades Contrast

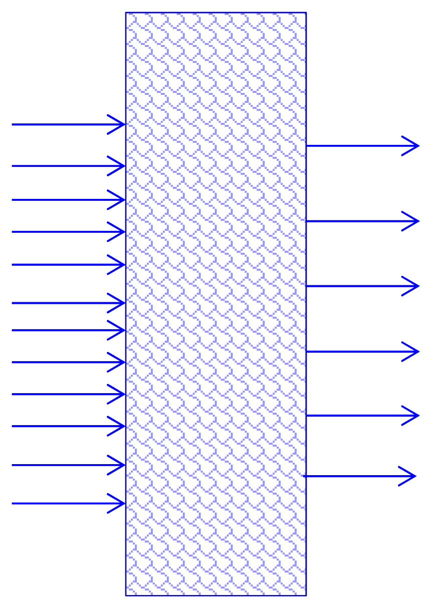


Without Scatter

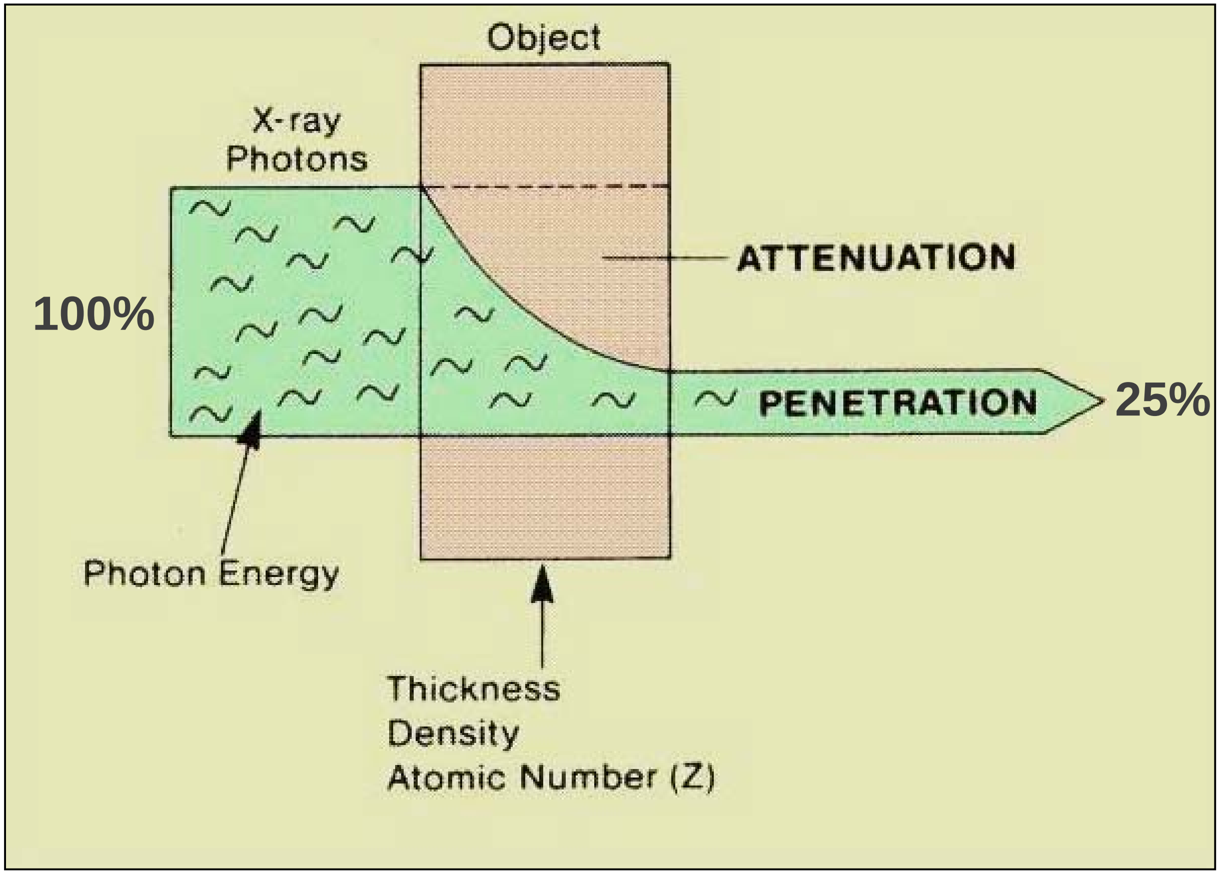
With Scatter

What is Attenuation?

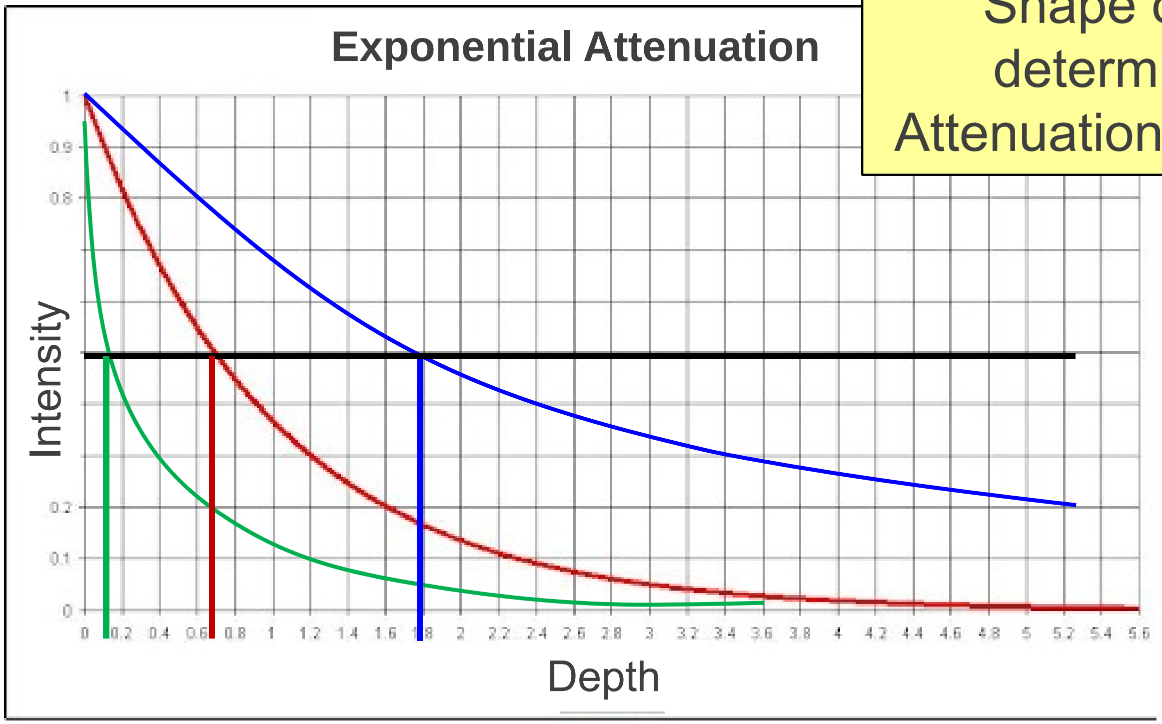
- Reduction of radiation as it passes through material
- Exponential reduction with thickness



Attenuation

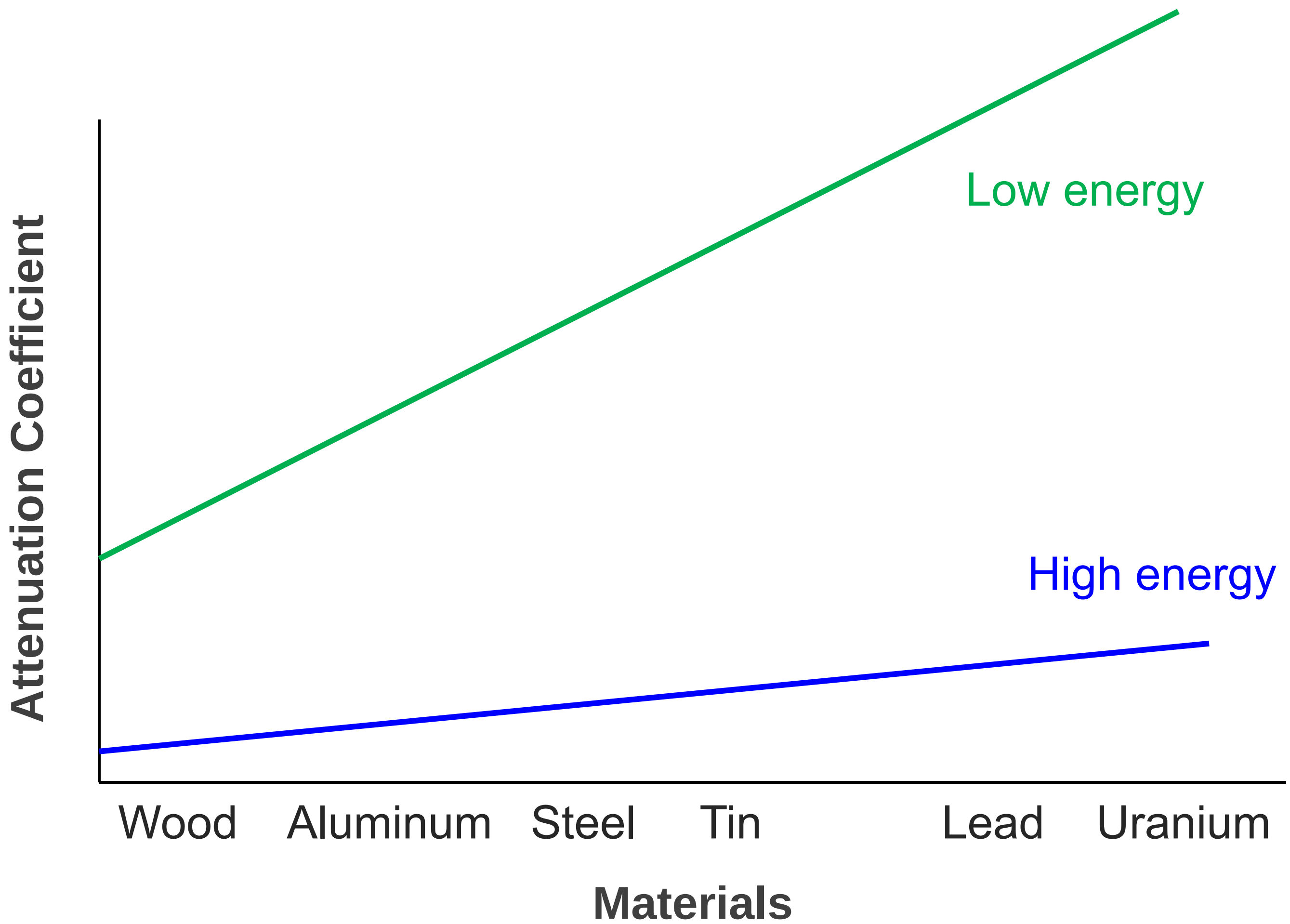


Exponential Attenuation

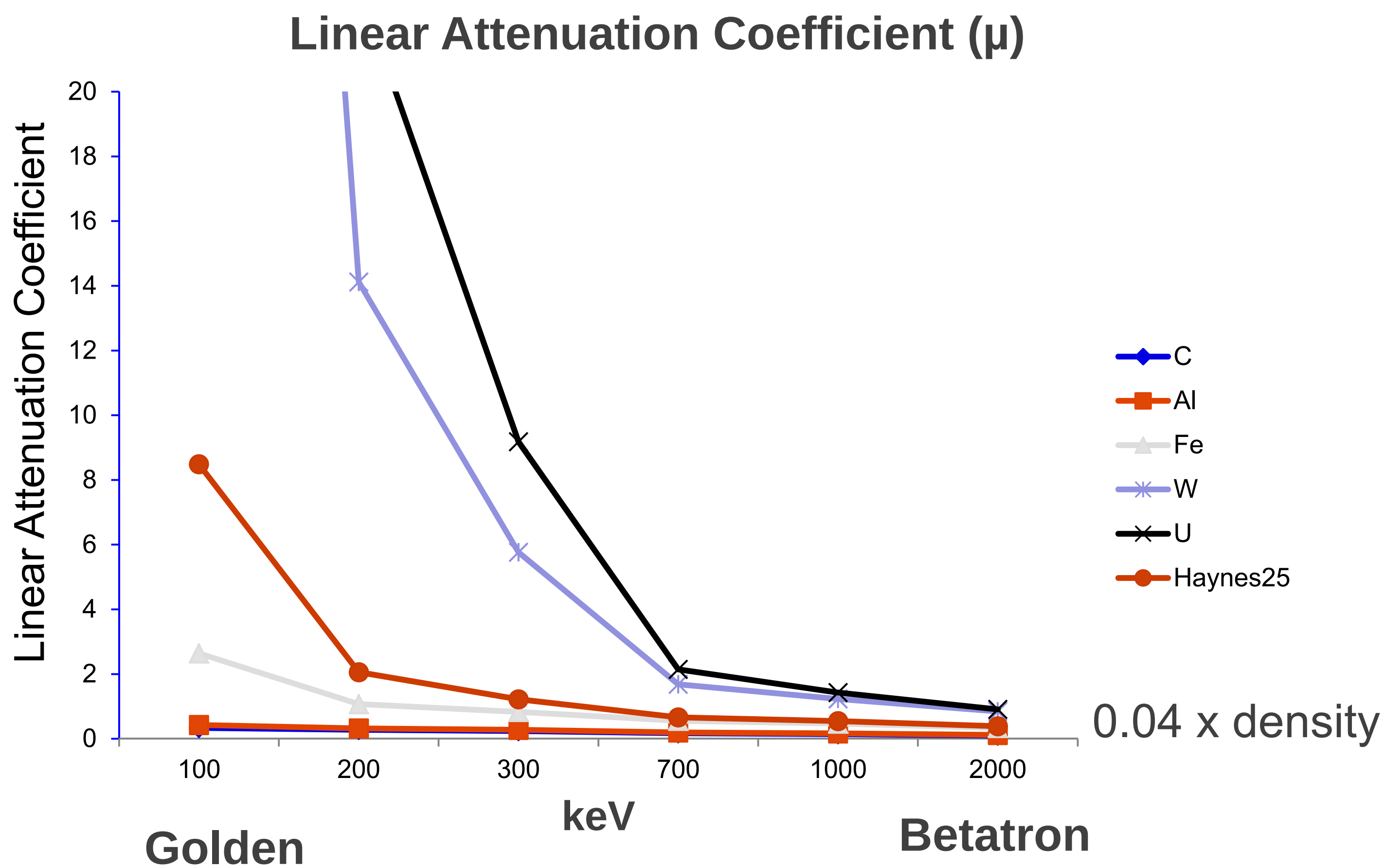


Shape of curve determined by Attenuation Coefficient

Attenuation by Material and Energy

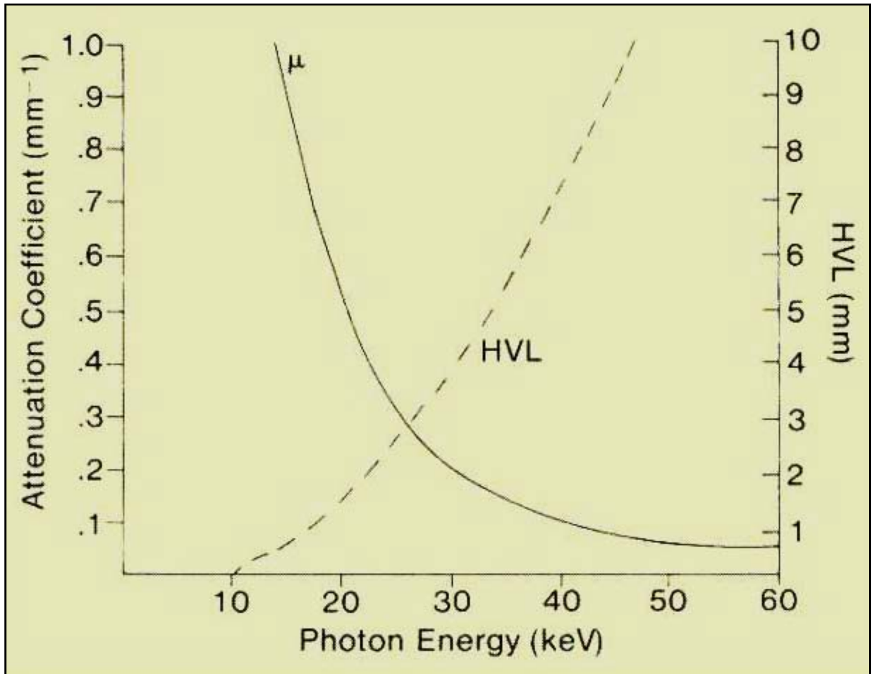


Attenuation Coefficient for Different Materials



Half Value Layer

$$\text{HVL} = \frac{0.7}{\mu}$$



Relationship between Attenuation Coefficient and HVL for Aluminum

If higher energy –

- Lower μ (less probability of interaction)
- Higher HVL (takes more material to stop x-rays)

Attenuation by HVLs

$$N = N_0\,(½)^{\#\ \mathrm{HVLs}}$$

For multiple materials:

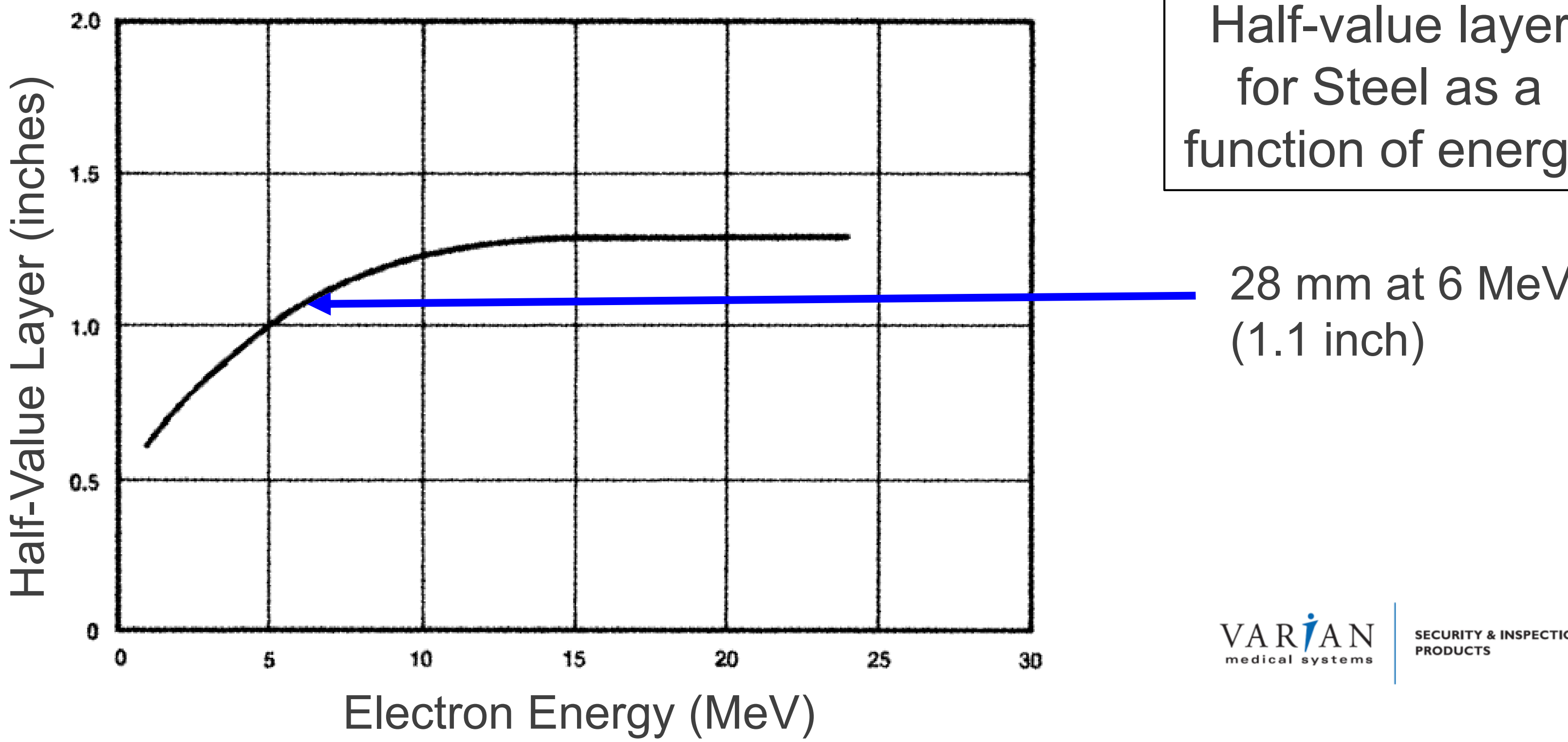
$$N = N_0\,(½)^{\#\ \mathrm{of\ HVL1}}\,(½)^{\#\ \mathrm{of\ HVL2}}\,(½)^{\#\ \mathrm{of\ HVL3}}$$

Material 1

Material 2

Material 3

HVL of Steel

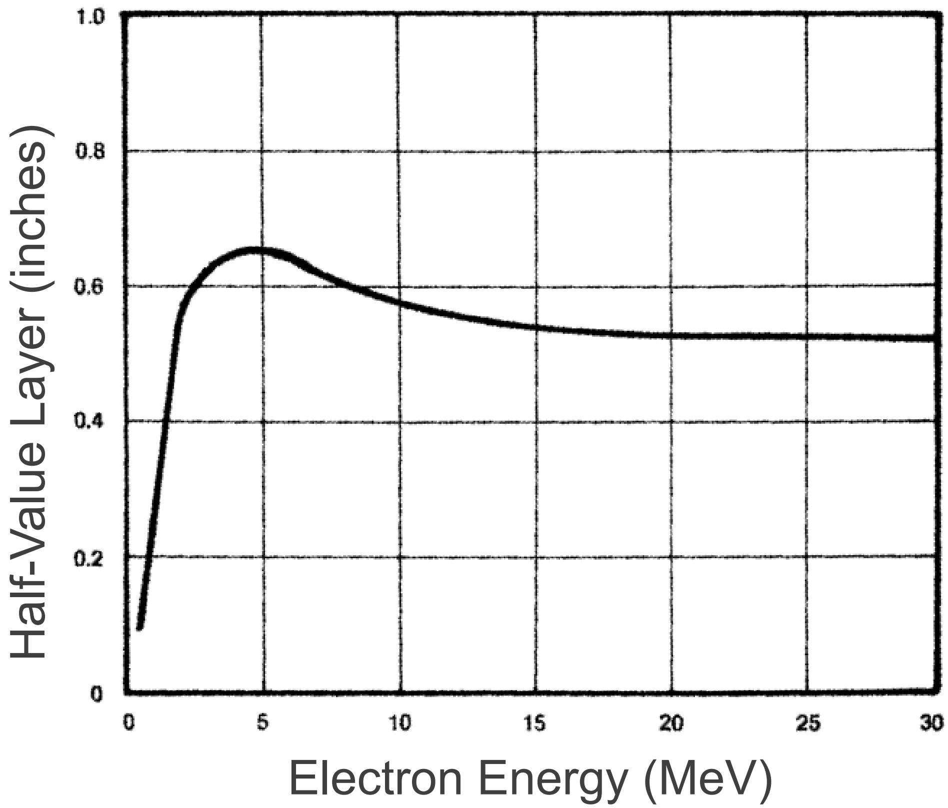


Half-value layer for Steel as a function of energy

VARIAN medical systems | SECURITY & INSPECTION PRODUCTS

Varian Linatron High-Energy X-ray Applications

HVL of Lead



Half-value layer for Lead as a function of energy

Varian Linatron High-Energy X-ray Applications

HVL of Some Materials

	XRS-3	Betatron	
	300 kV	2 MV	6 MV
Aluminum	25 mm	53 mm	89 mm
Steel	8.5 mm	20 mm	29 mm
Explosive		84 mm	137 mm
Tungsten		9 mm	13 mm
Lead	1.3 mm	13 mm	15 mm
U / Pu		7.5 mm	10 mm
Concrete	30 mm	63.5 mm	101.5 mm
Plastic		122 mm	198 mm
Water	58 mm	140 mm	241 mm
Air	51 m	124 m	204 m

HVL of Some Materials

	300 kV	2 MV	6 MV
Aluminum	1 inch	2.1 inches	3.5 inches
Steel	8.5 mm	[redacted]	1.1 inch
Explosive		[redacted]	5.4 inches
Tungsten		[redacted]	0.5 inch
Lead	1.3 mm	0.5 inch	0.6 inch
U / Pu		0.3 inch	0.4 inch
Concrete	30 mm	2.5 inches	4.0 inches
Plastic		4.8 inches	7.8 inches
Water	58 mm	5.5 inches	9.5 inches
Air	51 m	124 m	204 m

HIDDEN SLIDE

“Rule of Thumb”

Radiography works well for attenuation from ~2.5 to ~10 HVLs

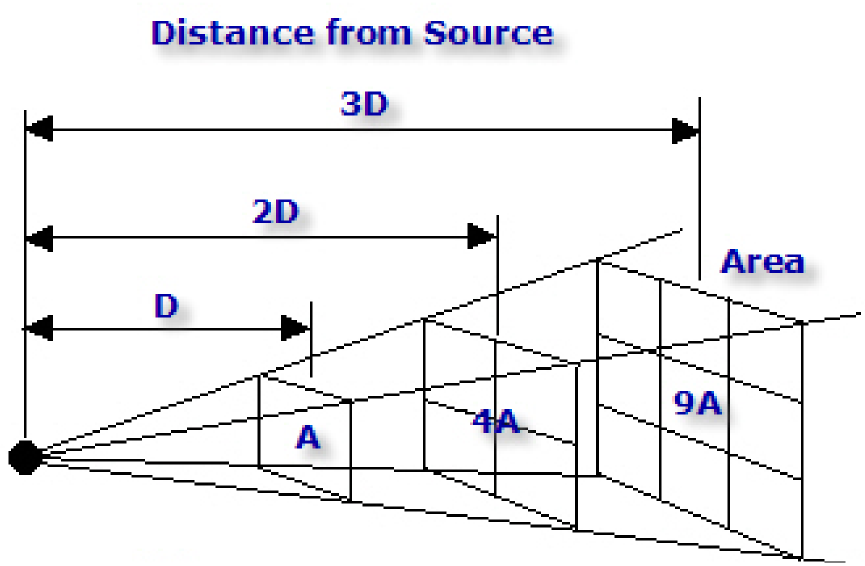
Successfully performed 6MV radiography through 368mm (14.5 in) of steel!

368mm/38mm = 13.2 HVLs

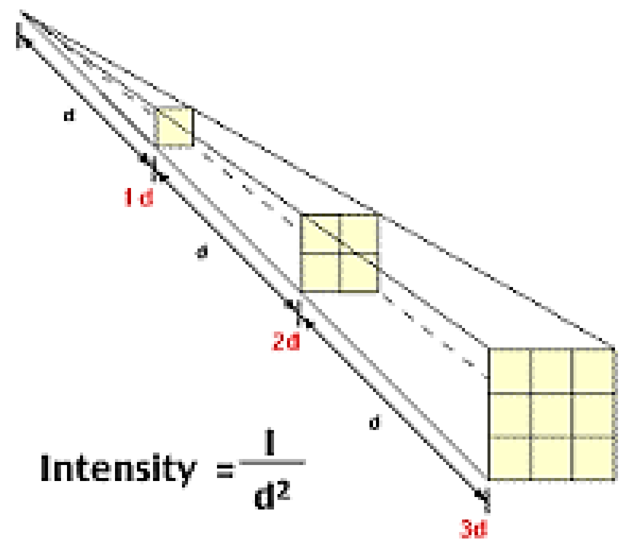
$2^{-13.2}$ = 0.0001 or 1/10,000

Inverse Square Law

Who can explain it?



Intensity **N** **N/4** **N/9**



Examples

Is there an object inside a

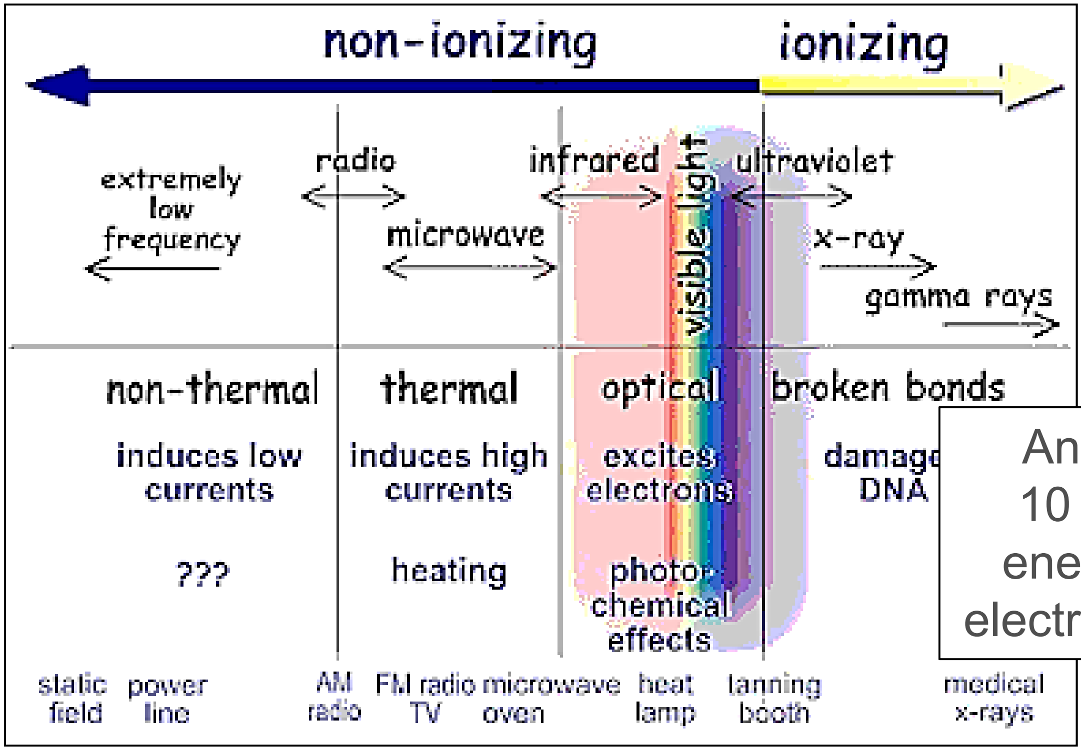
- Lead-lined steel drum 1.5 meters from the Betatron?

Ionizing Radiation

10 MeV to 100 eV

$\lambda = 10^{-8}$ to 10^{-13} m

$f = 3\times10^{16}$ Hz to 3×10^{22} Hz



Anything above 10 eV – enough energy to liberate electrons from atoms

Radiation Units Review

	CGS unit	SI unit
Exposure	Roentgen (R)	Coulombs/kg Or Gray (air)
Absorbed Dose	Rad	Gray (Gy)
Equivalent Dose	Rem	Sievert (Sv)

For x-rays

1 Rad ~ 0.01 Gy
1 Rem ~ 0.01 Sv

Lethal Dose in 50% of people = 4 Sv = 400 Rem

Occupational Dose Limits

- **U.S. Department of Energy (DOE)**
  - Effective dose limit = 50 mSv (5 Rem) per year
  - Public dose limit = 1 mSv (100 mrem) per year

Occupational Dose Limits (cont'd)

- **Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)**
  - Effective dose limit = 20 mSv per year, averaged over a period of 5 consecutive calendar years
  - Effective dose limit in a single year = 50 mSv
  - Public dose limit = 0.5 mSv per year

Boundaries

- **US Dept of Energy**
  - Controlled Area = 20 µSv (2 mR/hr)
  - Radiation Area = 50 µSv (5 mR/hr)
  - High Radiation Area = 1 mSv (100 mR/hr)
  - Very High Radiation Area = 5 Sv (500 R/hr)

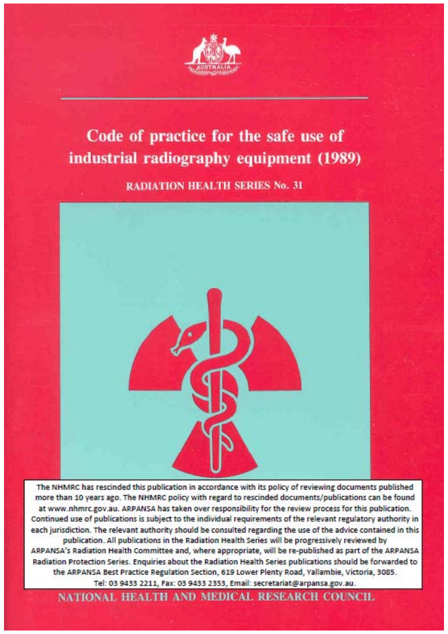
Boundaries (cont'd)

Australia RHS No. 31

- *Code of Practice for the Safe Use of Industrial Radiography Equipment (1989)*
- "Open Site" rules
  - Before commencing radiography operations at an open site, a well defined and clearly visible boundary shall be erected using warning signs and devices such as barriers, flagged rope, etc., around, above and below the site as appropriate. Boundary at

    25 μSv/hr (2.5 mrem/hr)

  - One or more warning lights and an audible alarm located immediately adjacent to the exposure position shall be used to indicate when an exposure is underway



Radiation Measurements

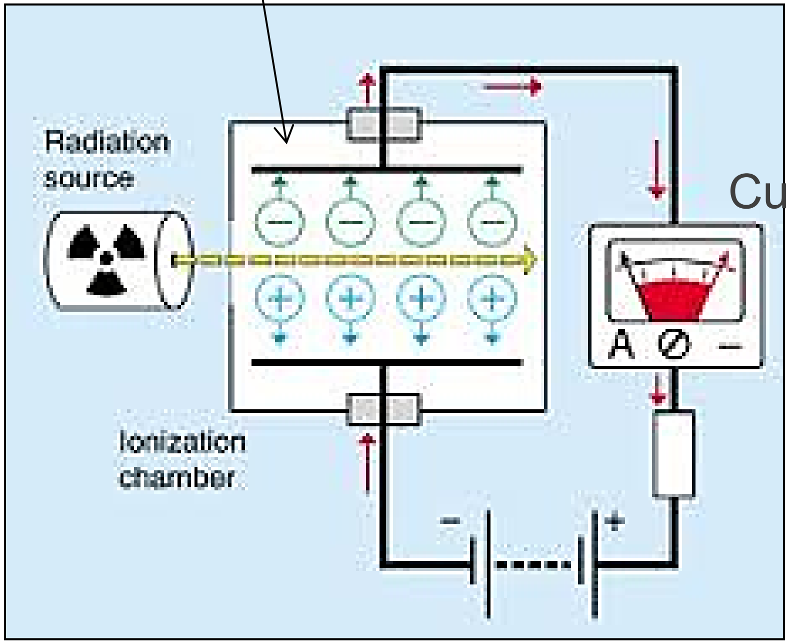
- Ion chamber
- G-M tube
- Electronic

Ion Chamber

Best instrument for radiography

Fluke

Air or Gas filled tube



Current Meter

Bias Voltage

Direct Reading Dosimeters

NOTE: Electronic dosimeters are not recommended for pulsed radiation unless specifically designed for pulsed

Lesson Summary

- Scatter, if detected in an x-ray image, affects the image's detail and sharpness
- The high energy output of the Betatron makes it effective at penetrating dense material
- Radiography works well for attenuation from ~2.5 to ~10 HVLs
- The occupational effective dose limit in a single year is 50 µSv (5 mR/hr) – Australia & U.S.
- The U.S. Dept of Energy regulations require a radiation Controlled Area to be at 20 µSv (2 mR/hr)

[redacted]

Extra Slides for Instructor Only

Practical

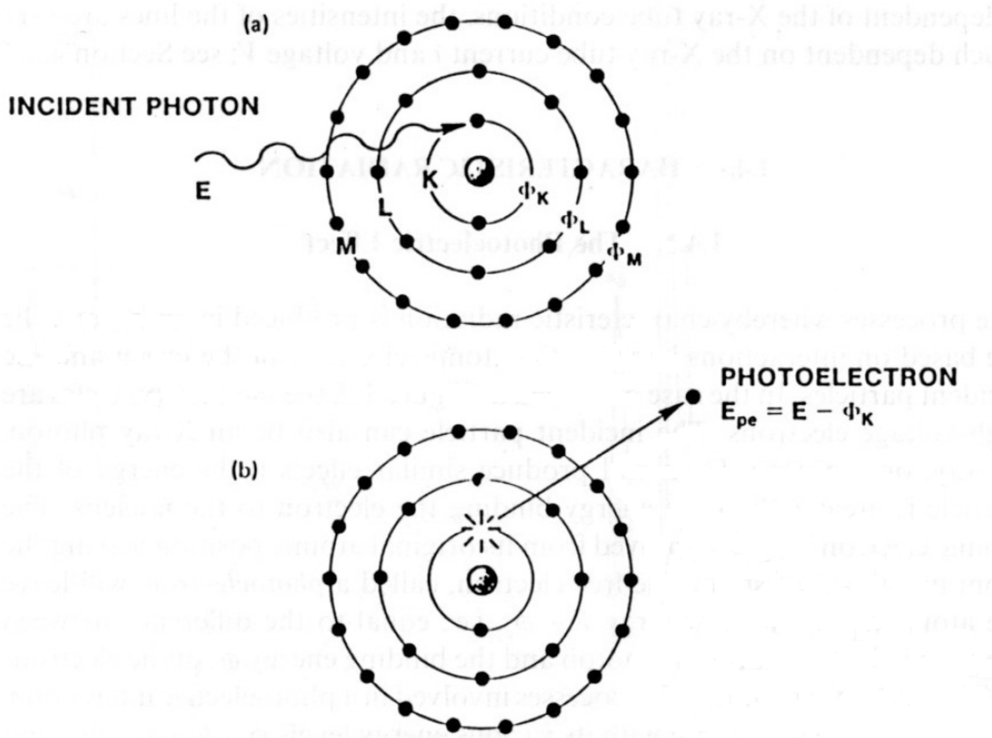
- Instructors will setup and operate Betatron
- Students will develop radiation safety brief
  - controls
- Measure Betatron output at different energies
- Students will determine 2.5 μSv/hr line (AUS)
- Students will determine 2, 5, and 100 mrem/hr lines (US)

Radiation Interactions

- Photoelectric Effect
- Compton Scattering
- Pair Production

Photoelectric Effect

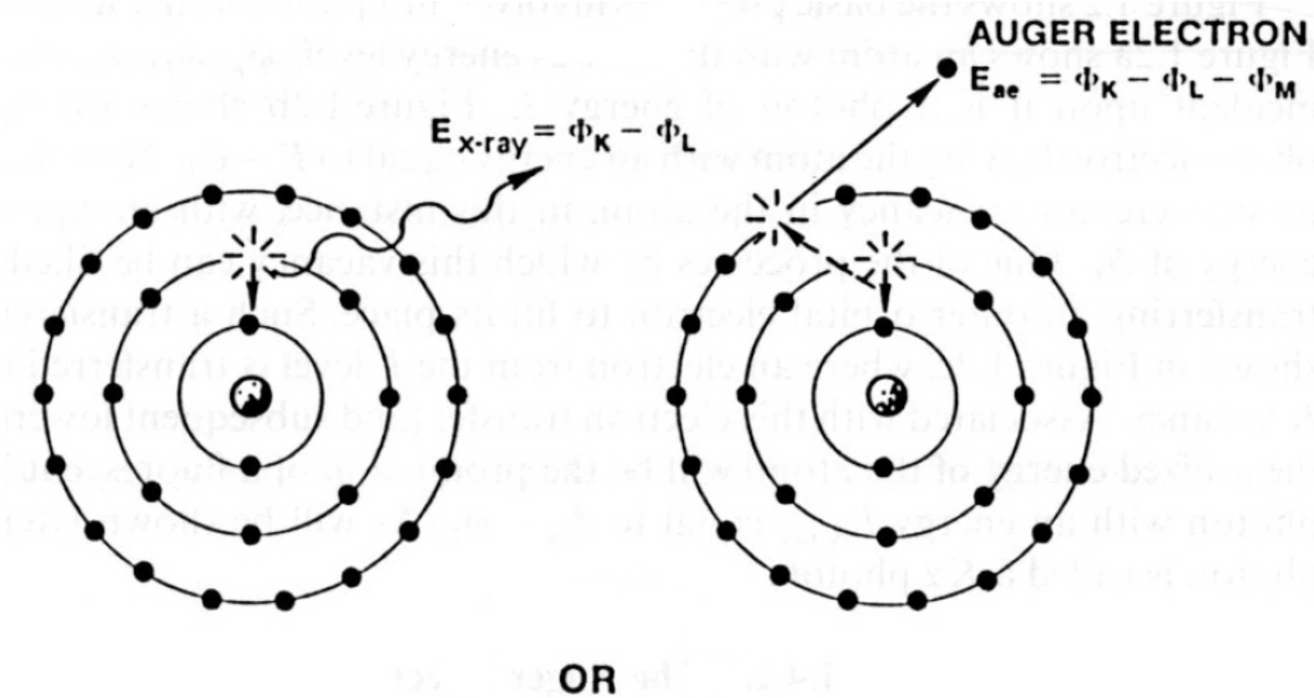
- Photon is completely absorbed and electron emitted



Photoelectric Effect

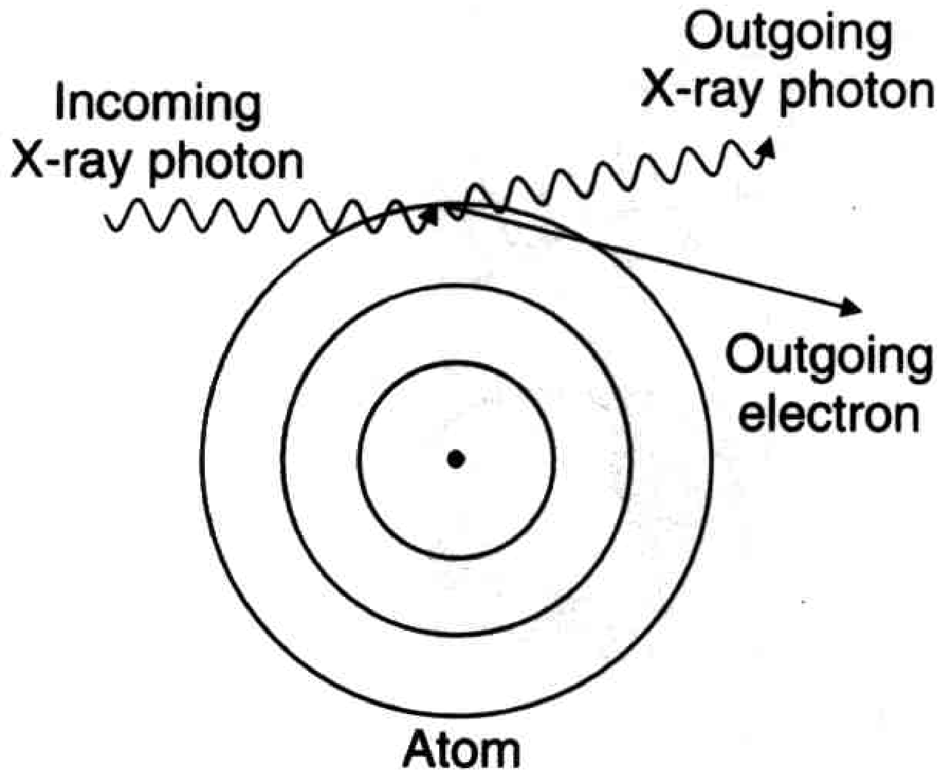
After effects of Photoelectric absorption

- Outer electron drops into ejected electron’s space and a secondary photon or electron is emitted



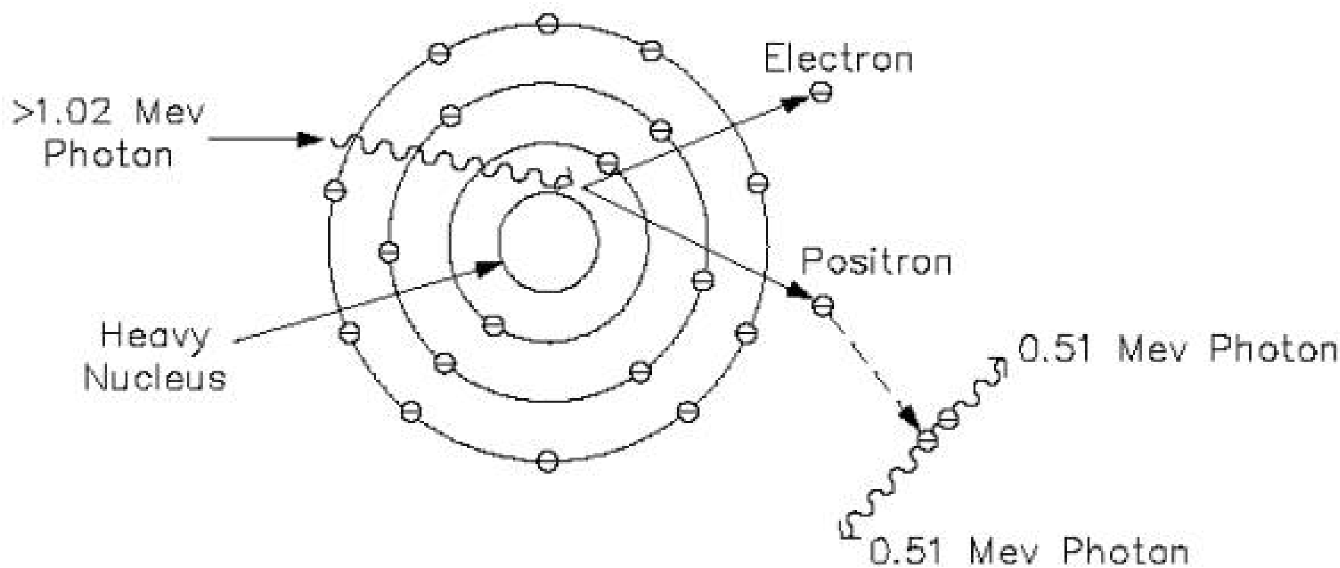
Compton Scattering

- Photon is scattered (loses part of its energy) and electron ejected

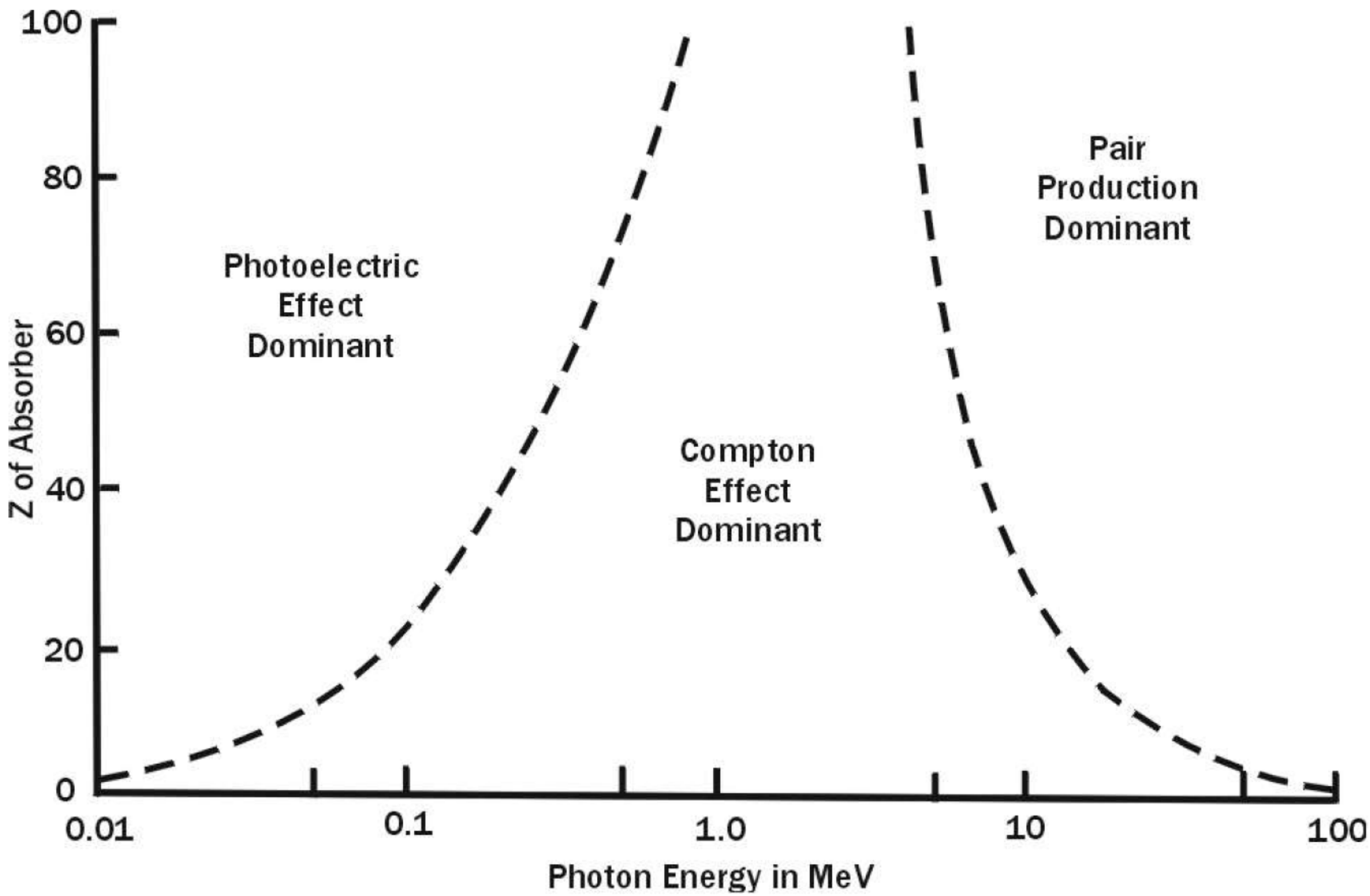


Pair Production

- Only occurs when photon is >1.02 MeV
- Electron and positron are created
- Positron annihilates and two 511 keV photons are created



Interactions vs. Photon Energy

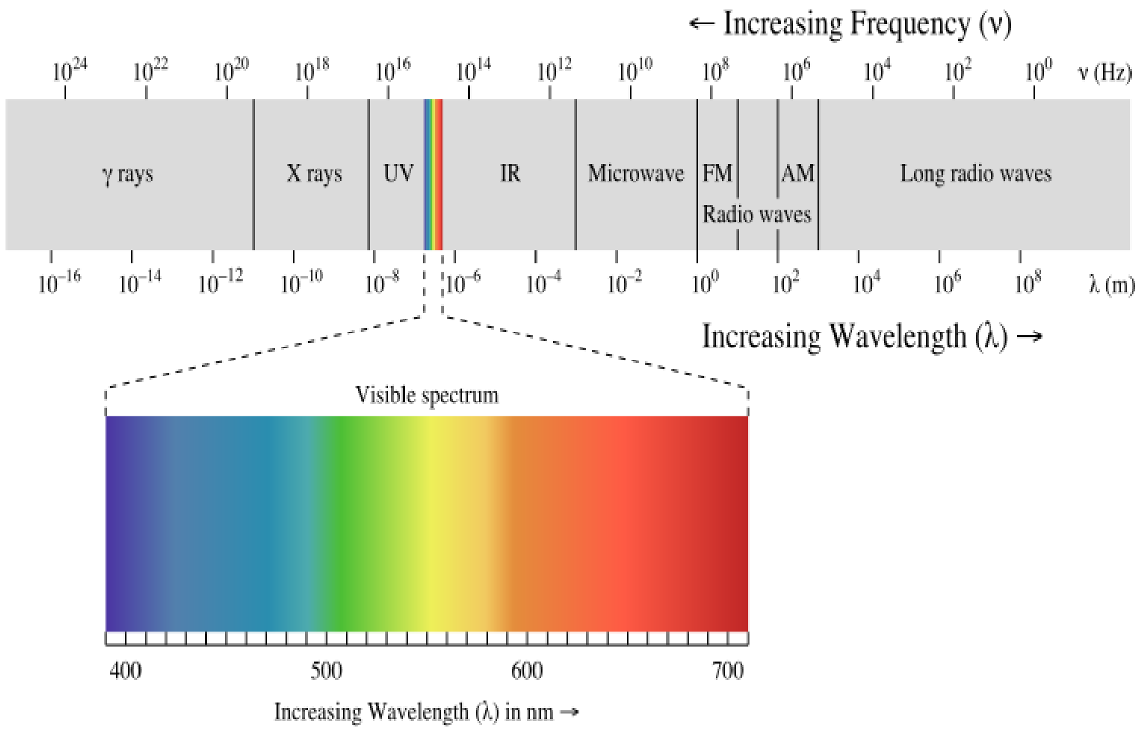


X-ray Generation

- X-rays are generated when charged particles slow down
- OR when electrons move within an atom
- In an x-ray machine electrons are accelerated and then smashed into a heavy metal target
- “Bremsstrahlung”: German for “breaking radiation”

X-rays

- **X-rays are electromagnetic radiation**
  - Radio waves
  - Microwaves
  - Infrared light
  - Visible light
  - Ultraviolet light
  - X and gamma



- **Dual particle (photon)/wave nature**

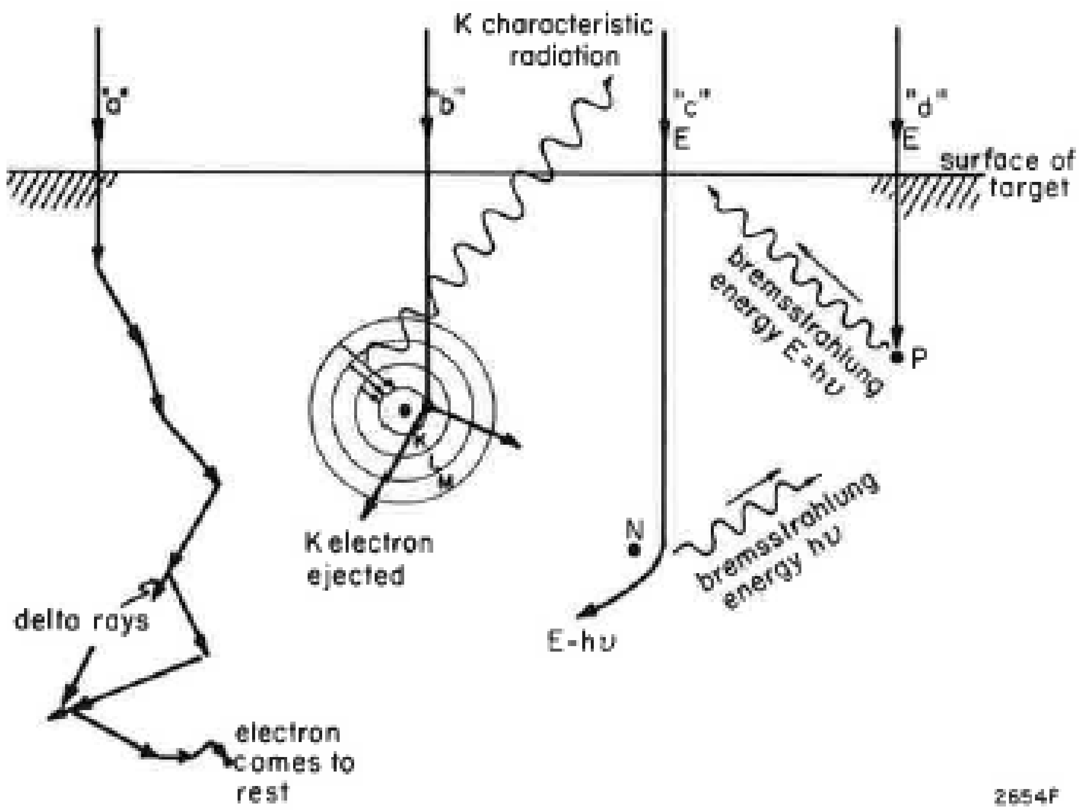
Electron Volts

- One Electron Volt (eV) is the amount of energy gained by one electron accelerated by one volt
- Equal to 1.6×10^{-19} Joules
- 1.6 eV to 3.4 eV: the photon energy of visible light
- 10^{9} eV is about the kinetic energy of a flying mosquito
- 10^{14} eV of energy of a typical rain drop

Electron Volts

- X-ray interactions concentrate keV magnitude energy into atomic scale
- Atoms are held together by keV magnitude energy

X-ray Generation



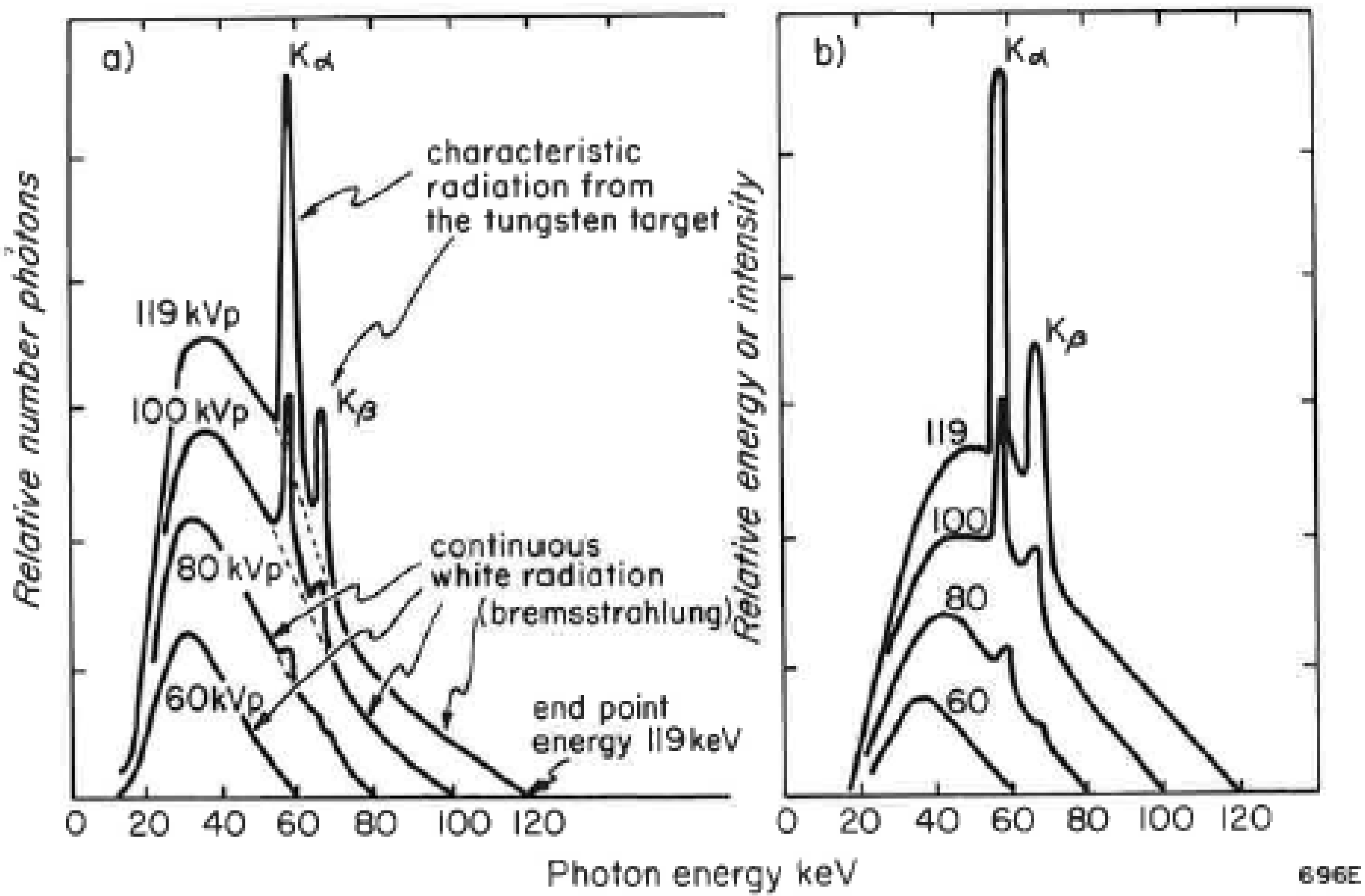
(a) Electron loses energy as heat

(b) Electron interacts with target electron

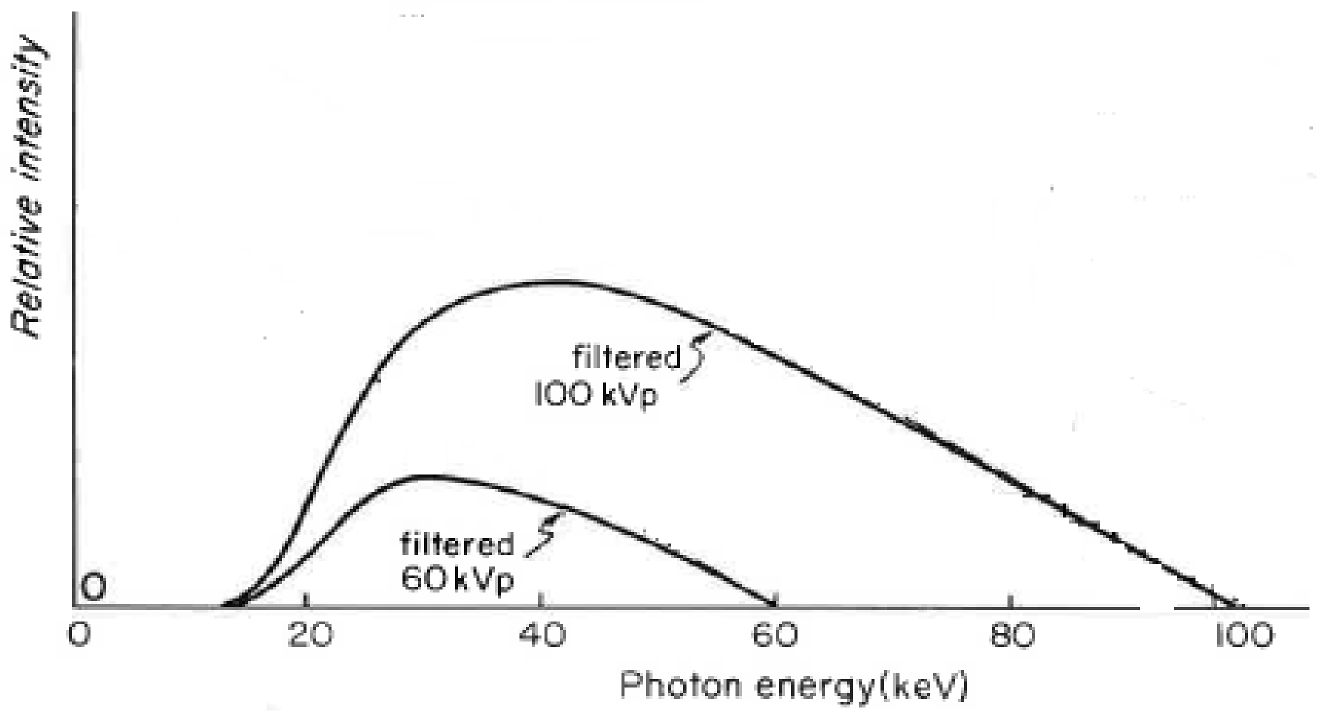
(c) Bremsstrahlung as electron gets deflected by target nucleus

(d) Bremsstrahlung as electron is stopped by target nucleus (very rare)

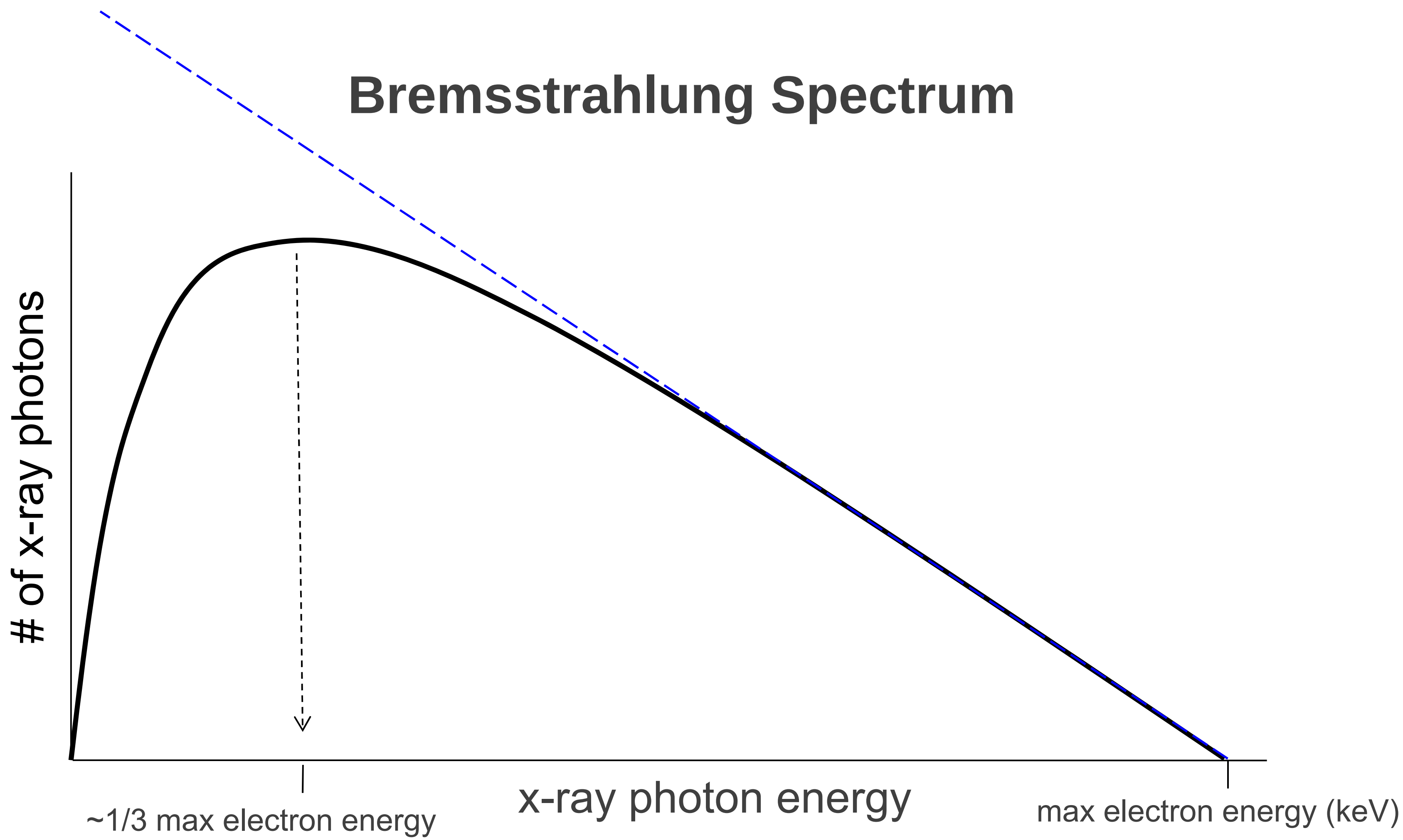
X-ray Spectra



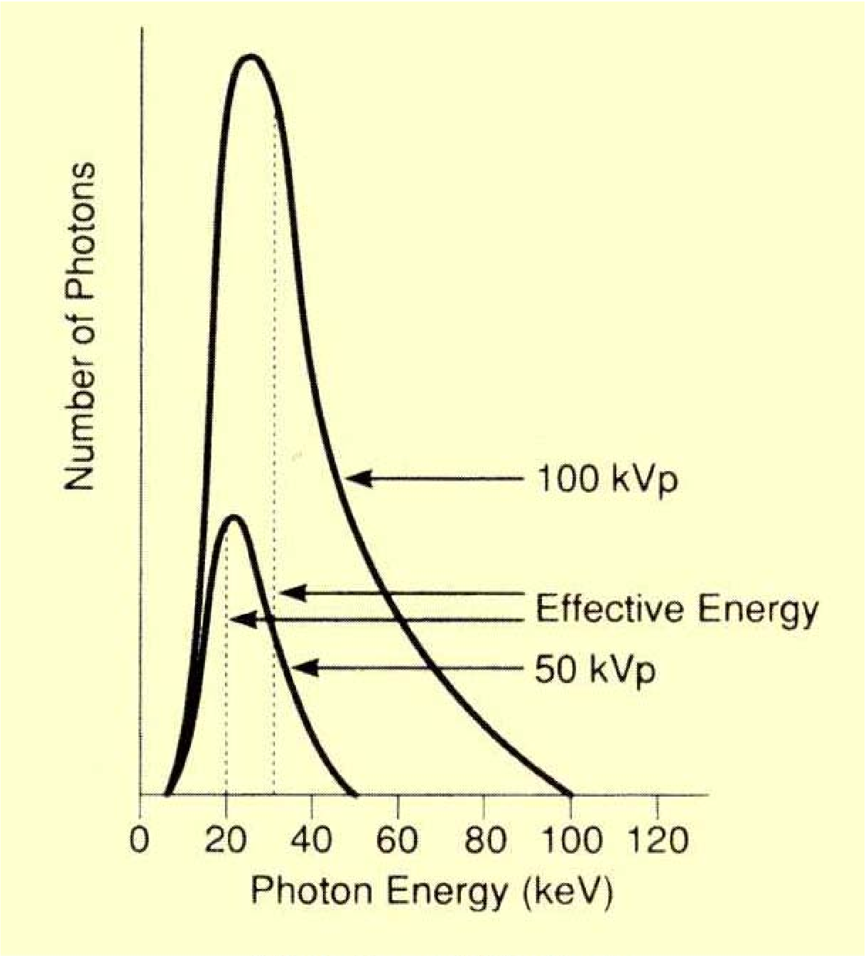
X-ray Filtering



X-ray Spectrum

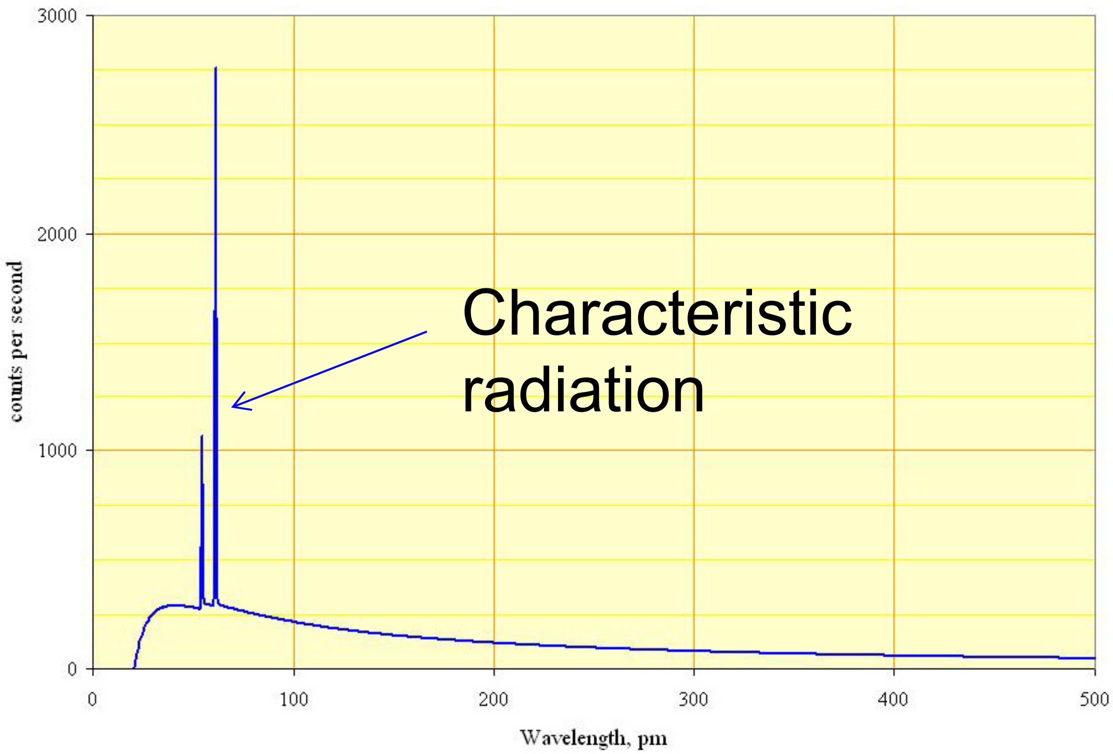


X-ray Spectrum Effective Energy



Effective Energy of X-Ray Spectra

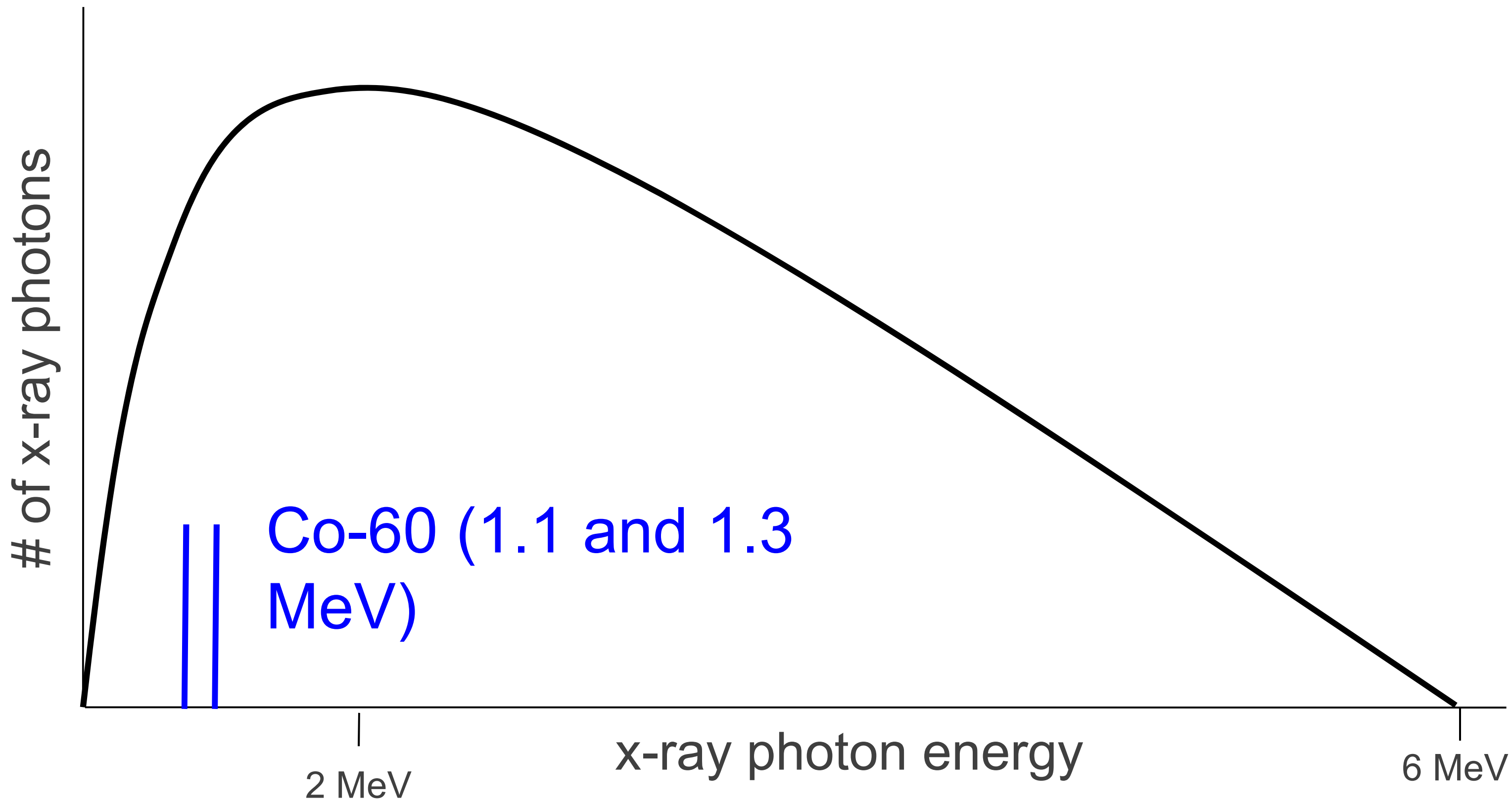
X-ray Tube Spectrum



Spectrum of the X-rays emitted by an X-ray tube with a rhodium target, operated at 60 kV. The smooth, continuous curve is due to *bremsstrahlung*, and the spikes are characteristic K lines for rhodium atoms.

X-ray Spectrum

- **Bremsstrahlung Spectrum (6 MeV)**

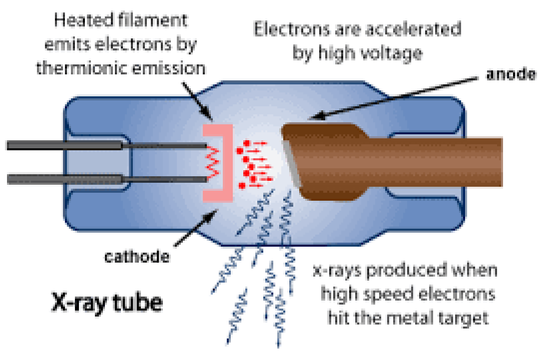


X-ray Machines

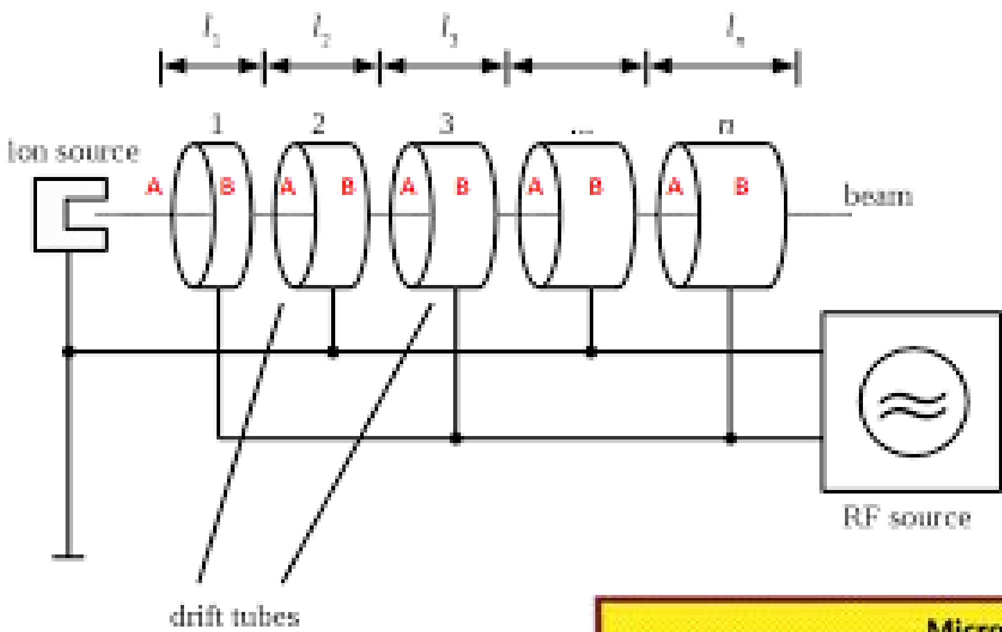
- Electrostatic Generators (<600 keV)
- Linear Accelerators (1 to 20 MeV)
- Circular Accelerators (1 to 50 MeV)

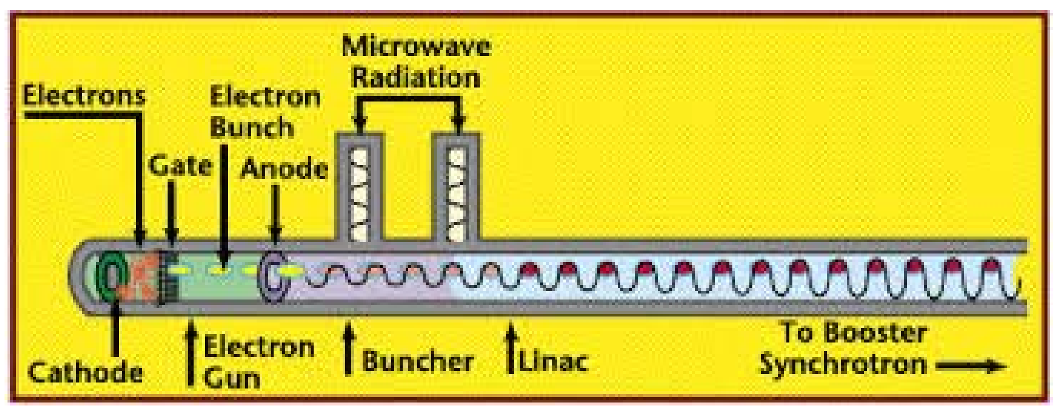
Electrostatic Machines

- Cold Cathode (Golden)
- Heated Filament



Linear Accelerators





STABILIZATION PROGRAM
NNSA NA-42

Betatron Course

Lesson 3
Betatron Operation

Lesson Objectives

1. Identify **safety measures** when operating the Betatron
2. Identify **machine care** measures
3. Explain the basic principles of **how the Betatron works**
4. **Operate** the Betatron

Overview of Betatron Equipment

JME Betatron (PXB-6MJ)

X-ray Radiator Unit (Accelerator)

Power Unit

Remote Dosimeter

Laser Alignment Unite

Audio/Visual (HV) Warning Unit

Control Panel

Specs

Energies: 2.0 to 6.0 MeV in 0.1MeV steps

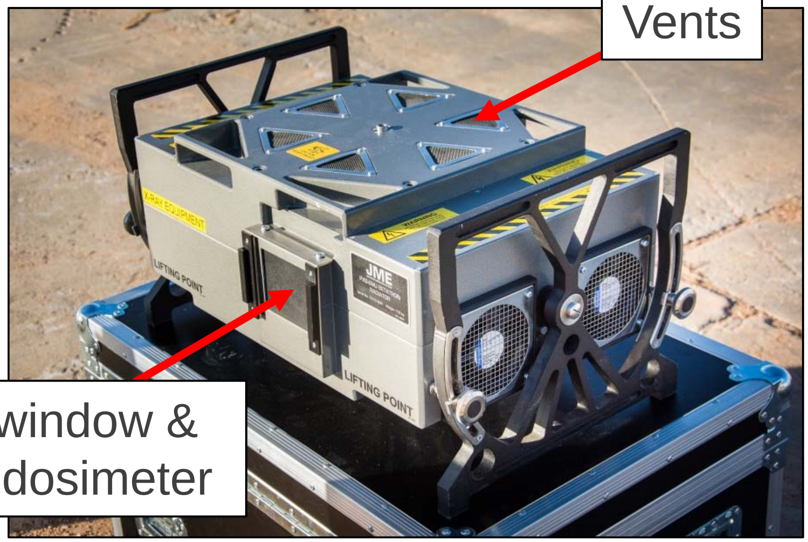
Output: Minimum 0.03 Sv/min @1m (3R)

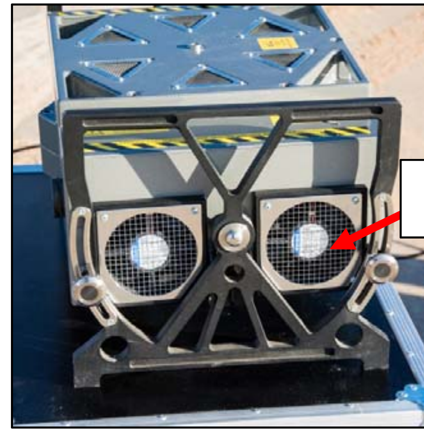
Focal spot: 0.3 x 3.0 mm

HVL steel: 28mm (6 MeV)

Power: 220/110v, 50/60Hz

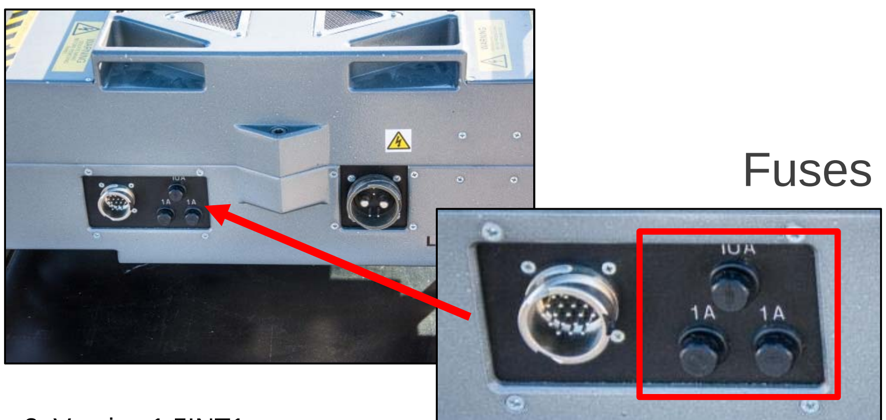
X-ray Radiator Unit





Legs are detachable

Fuses



Case

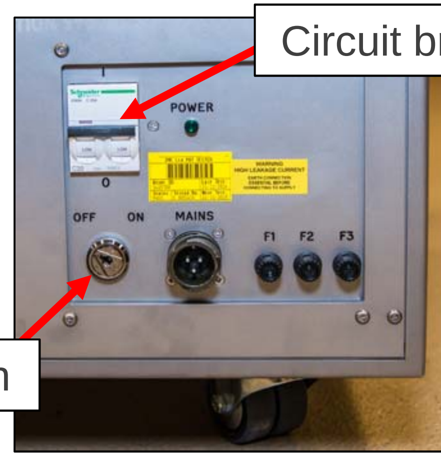
Power Unit

- Contains the main ‘bridge’ circuit, that applies power to the magnet coils in the x-ray radiator (peak voltage >1000V)
- Contains control circuits
- Powered from single-phase 110/230VAC

Power Unit (cont'd)

Connector panel

Circuit breaker



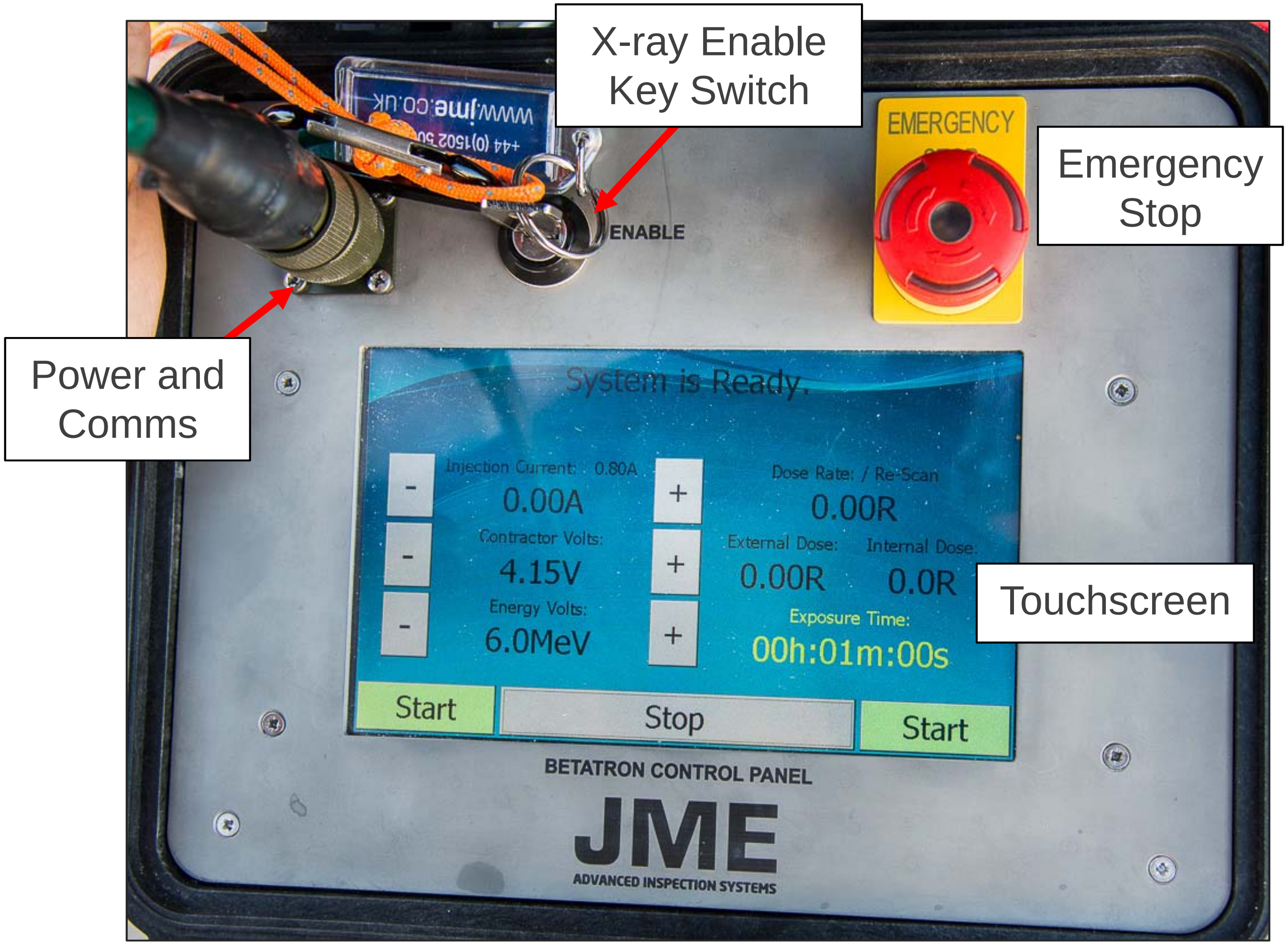
On/off key switch

Mains panel

Control Panel

- Provides a simple user interface
- Allows safe starting and stopping of radiation
- Allows certain radiation parameters to be adjusted

Control Panel (cont'd)



A/V Warning Unit

Green light flashes once Control Panel boots up

Amber light flashes for 10 seconds

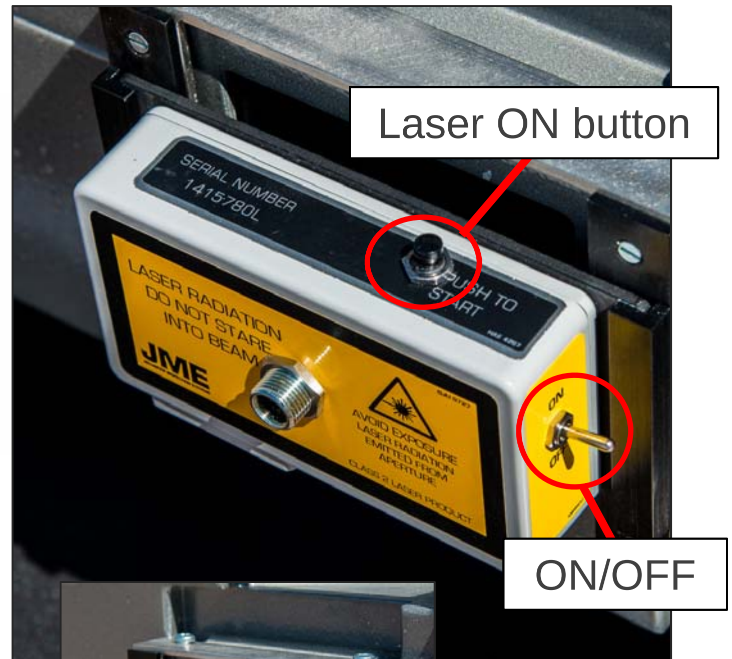
Red light stays on during entire radiation period

Interlock

If flashing lamp burns out, LED will light

Laser Alignment Unit

- **Power ON/OFF toggle**
- **Laser ON push button**
  - 60 second timer
- **9V Battery**
- **Do not stare Into beam and avoid reflections**
  - 0.8 mW
- **Remove before powering on Radiator**



Mounted to the X-ray Radiator

Remote Dosimeter

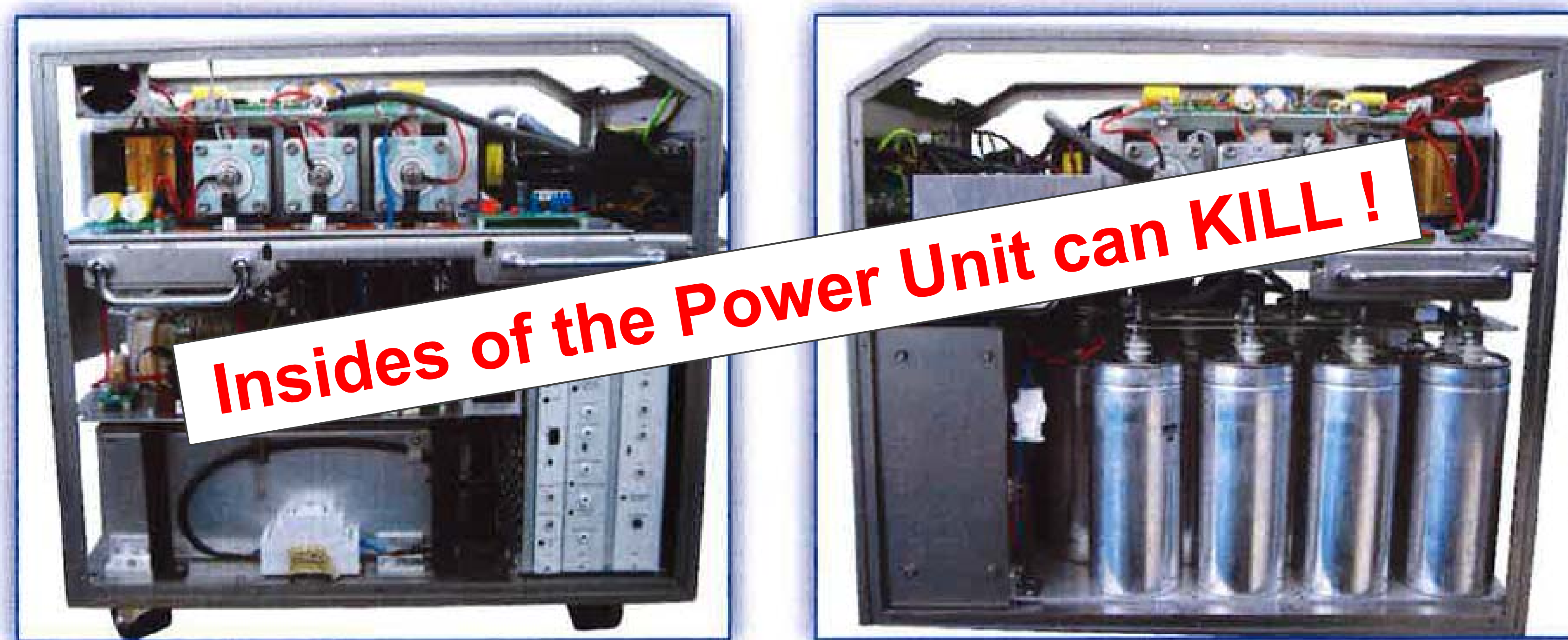
- Accumulated dose at target
- Can be used to terminate exposure when pre-set dose has been reached

Safety

Safety Issues

- **Radiological**
- **Electrical**
  - High voltages: shock/burn
  - Capacitors: lethal stored energy
    - Could retain charge for several hours
  - Some cables carry dangerous voltages when system is operational
- **Laser**
- **Lifting**
  - Back strain
  - Foot protection
  - Fingers: pinching
- **Needs “reasonably” clean and dry conditions**

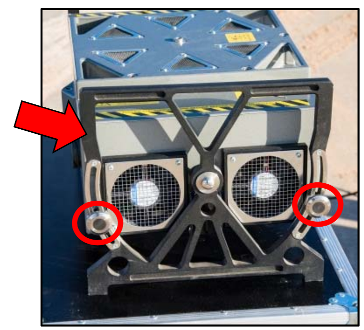
Electrical Hazards



Mechanical/Physical Safety

Lifting the Radiator

- **Requires two-person lift**
- **Lift at marked lifting points ONLY**
  - Ensure adjustable legs on the Radiator are fixed in position before lifting/moving
  - Insure thumbscrews are tightened



Adjustable Legs
Can use for lifting

Radiator Stand

Lifting straps properly applied

Mechanical/Physical Safety

Lifting the Power Unit

- Requires two-man lift using handles

Lifting straps properly applied

Machine Care

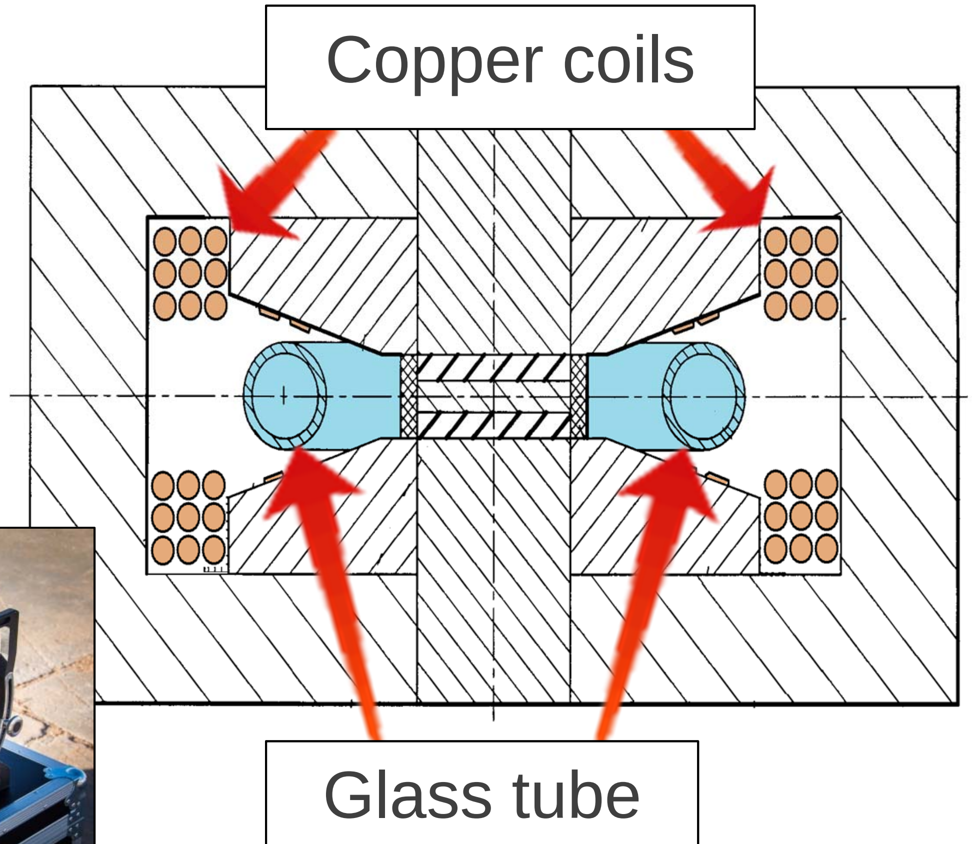
- **Ventilation grilles and fans must be kept clear at all times**
- **Protect from adverse environmental conditions (water and dust)**
  - Use a tent-like cover for rain or snow
  - If exposed to a dusty environment clean with a vacuum and wipe with a dry cloth
- **Maximum duty cycle for system is 75%, based on 45 mins on and 15 mins off**

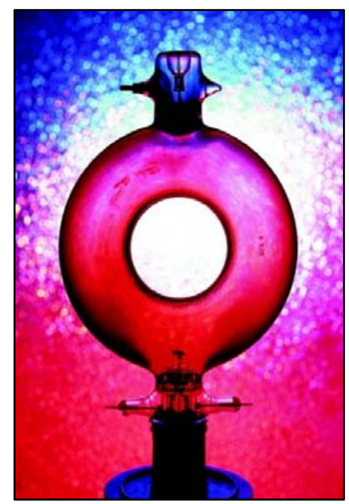
How does it work?

How it Works

Structure of X-ray Radiator

SIDE view

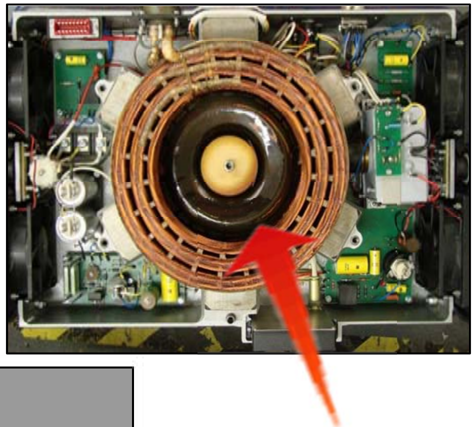


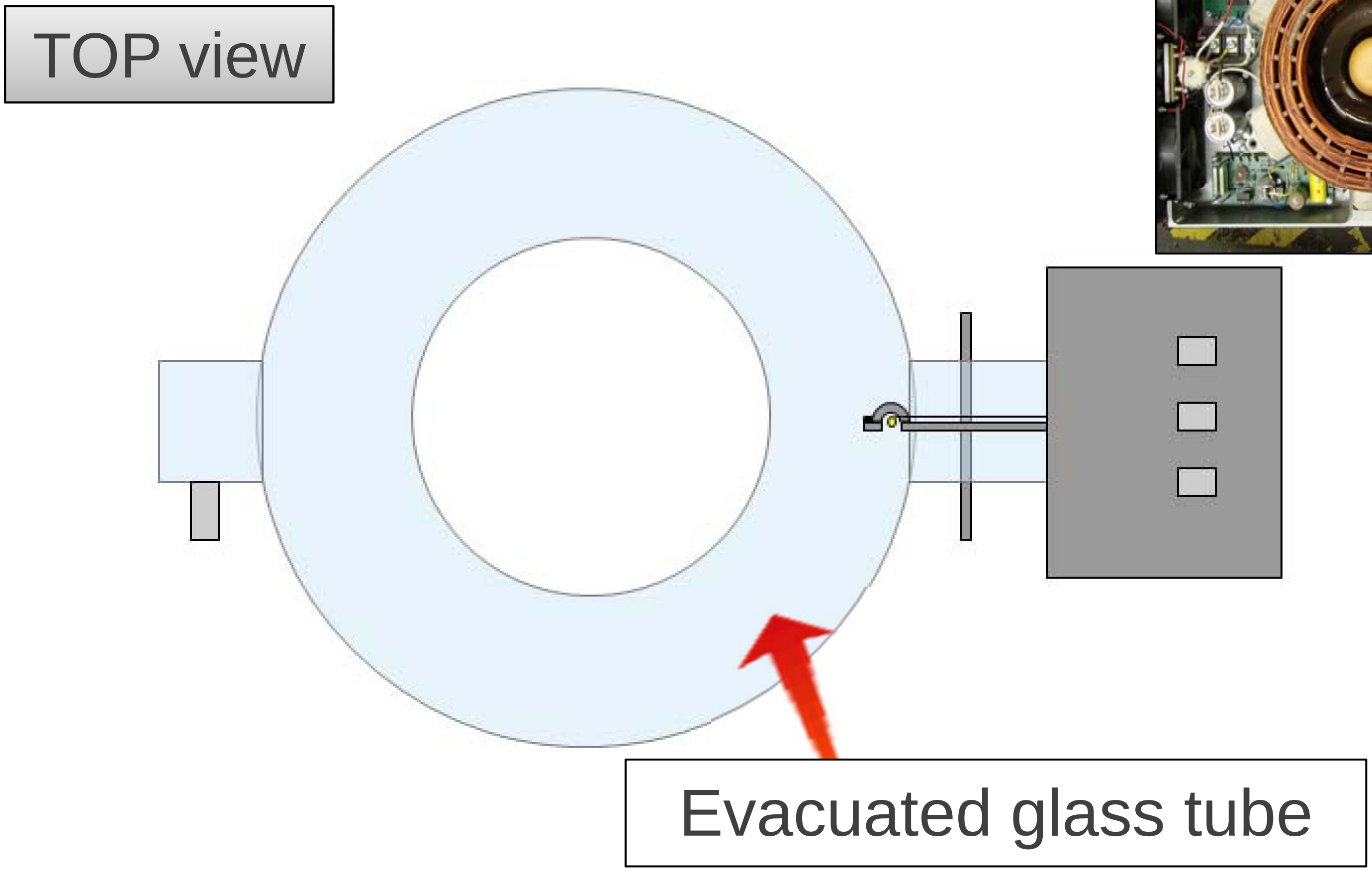


Glass tube

How it Works (cont'd)

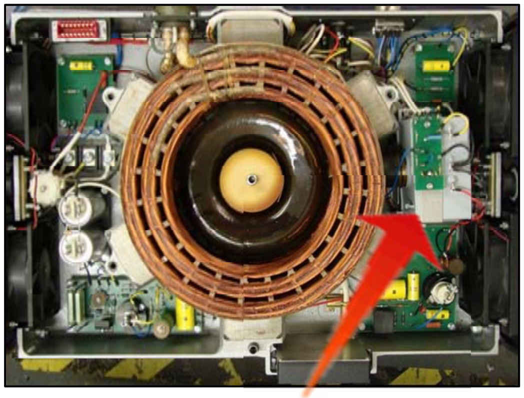
Structure of Tube

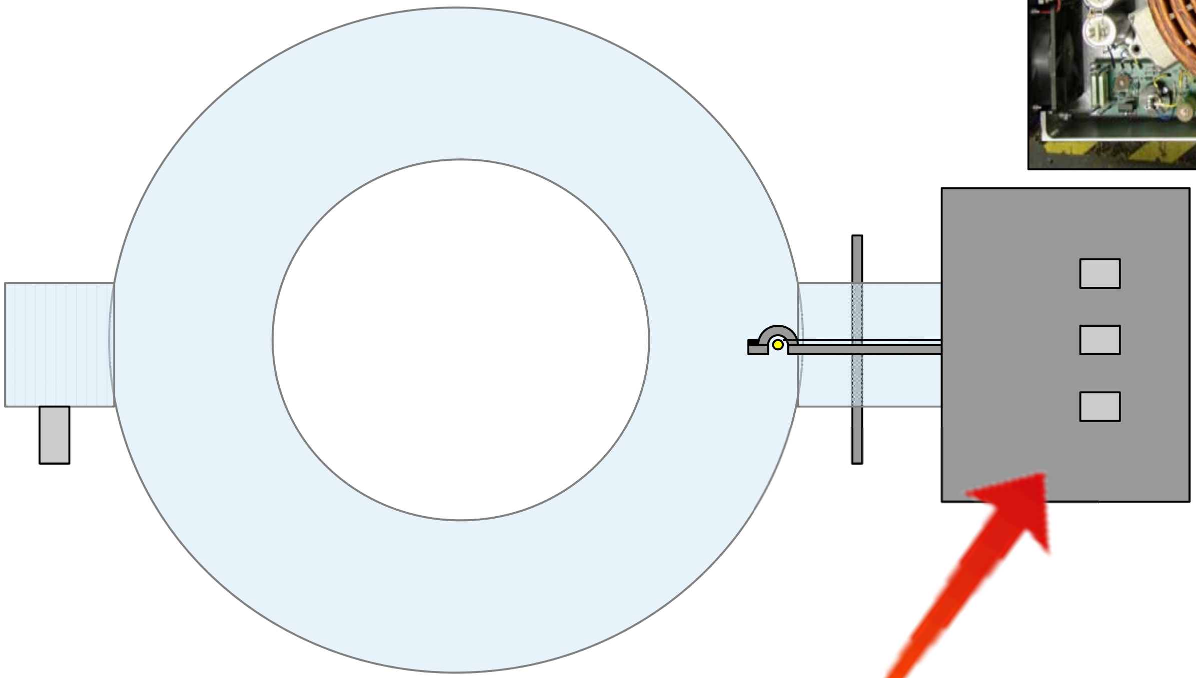




How it Works

Structure of Tube

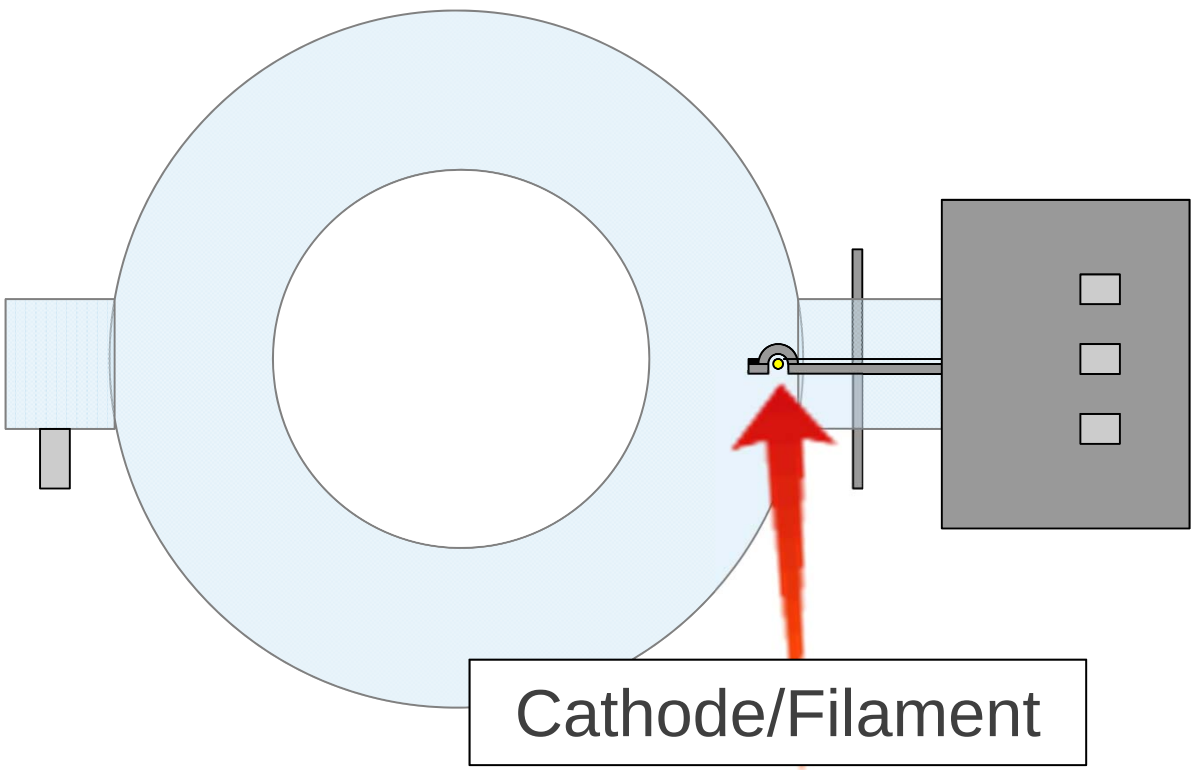




High voltage transformer

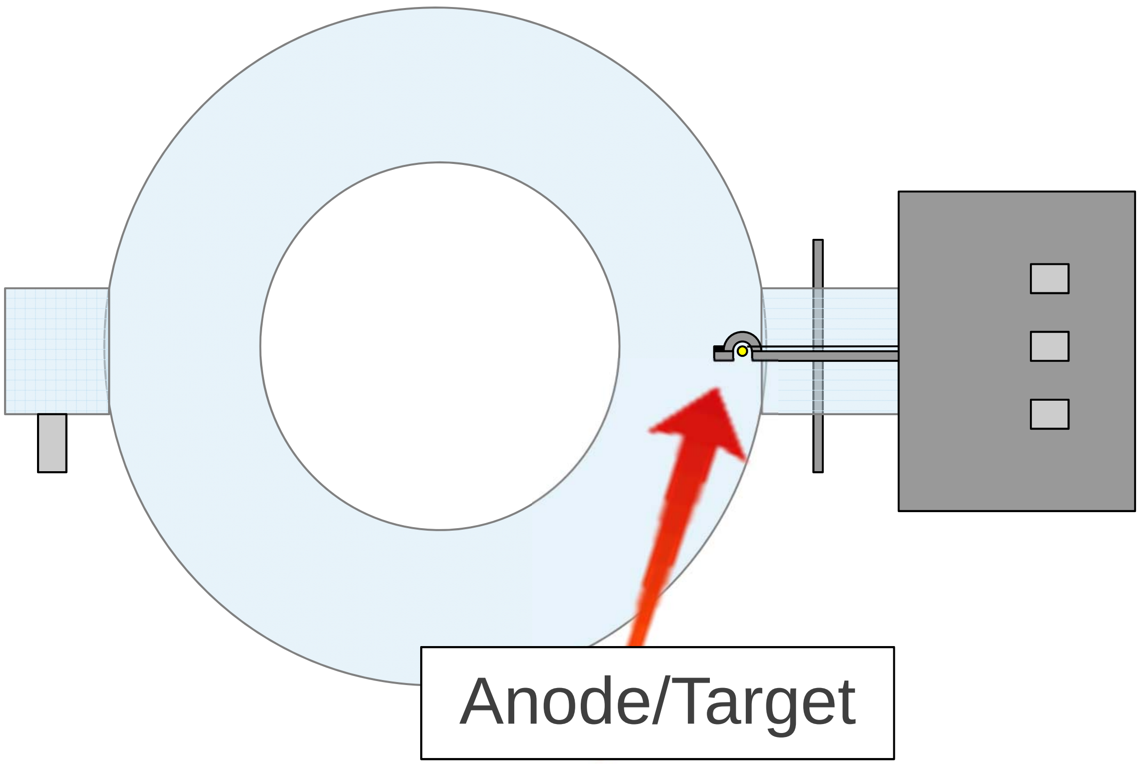
How it Works (cont'd)

Structure of Tube



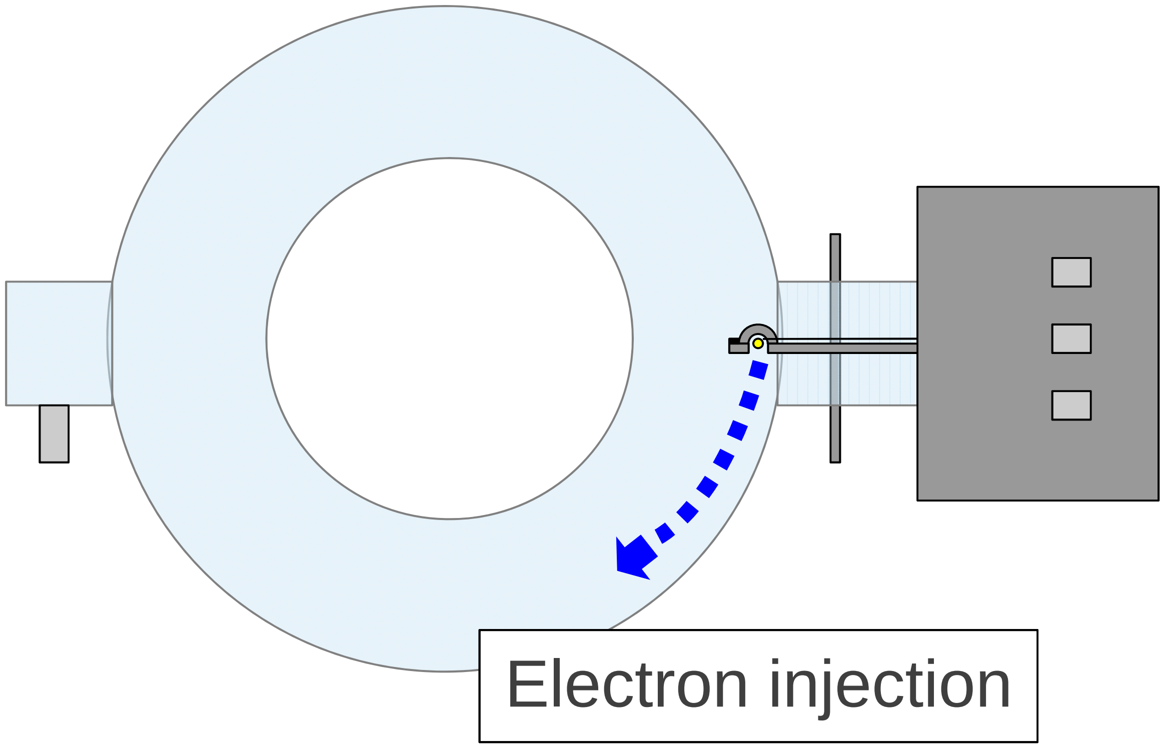
How it Works

Structure of Tube (cont'd)



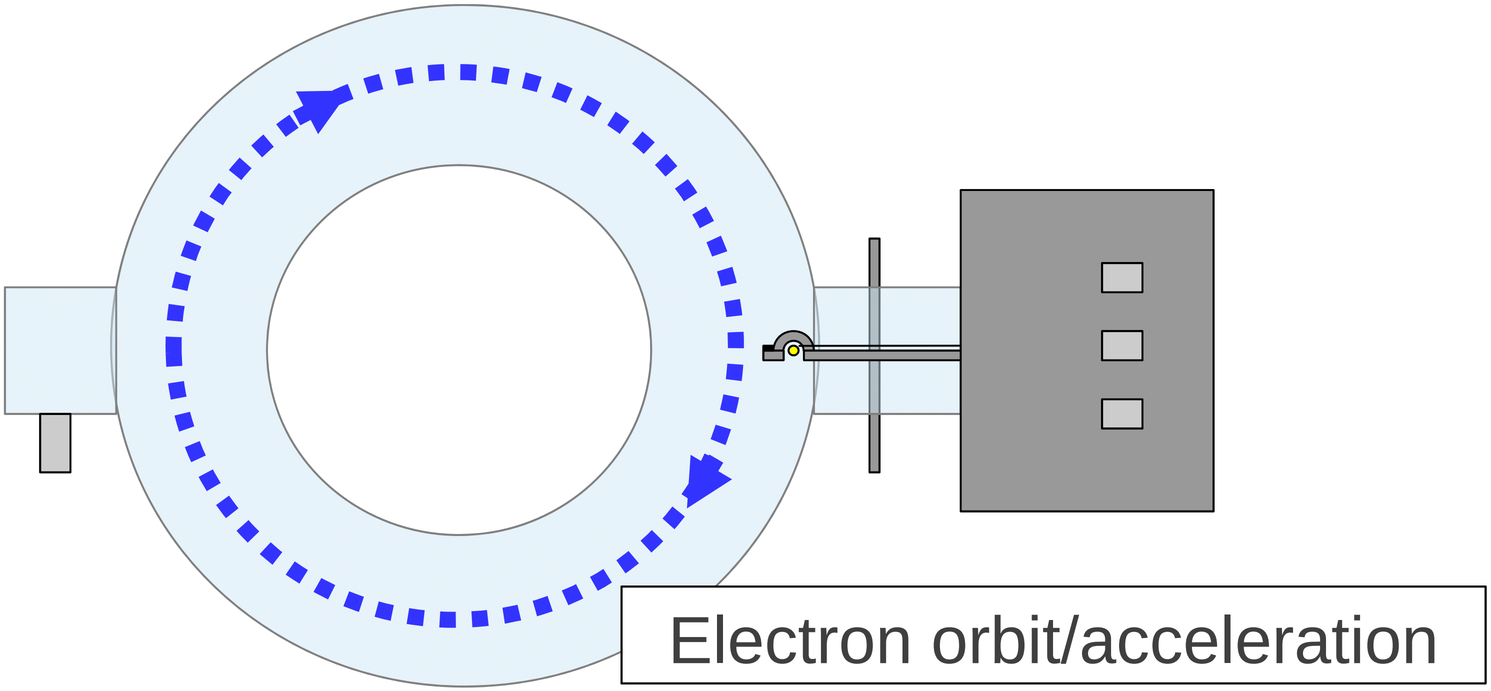
How it Works (cont'd)

How Electrons Move



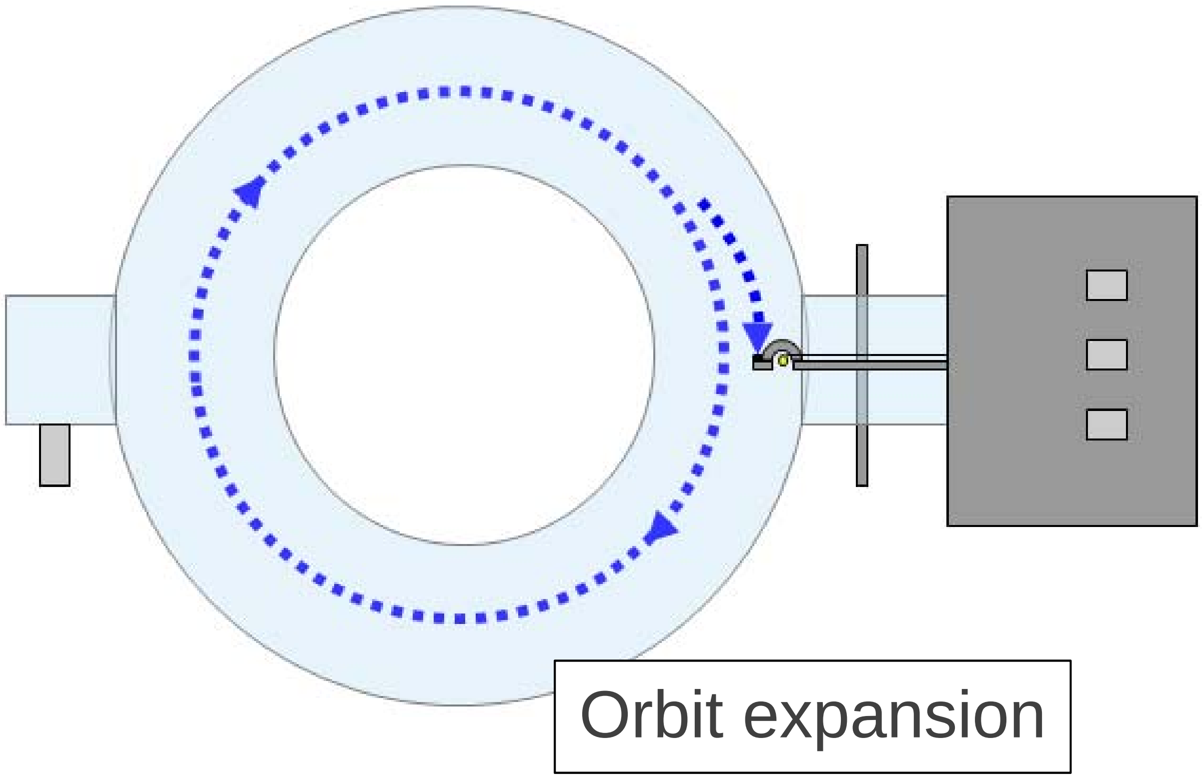
How it Works

How Electrons Move (cont'd)



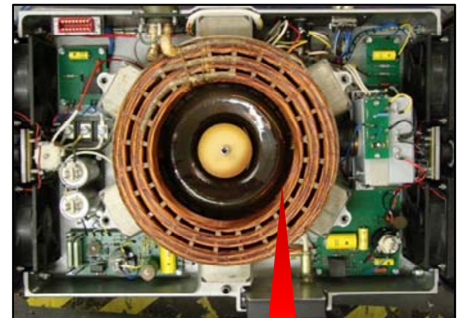
How it Works

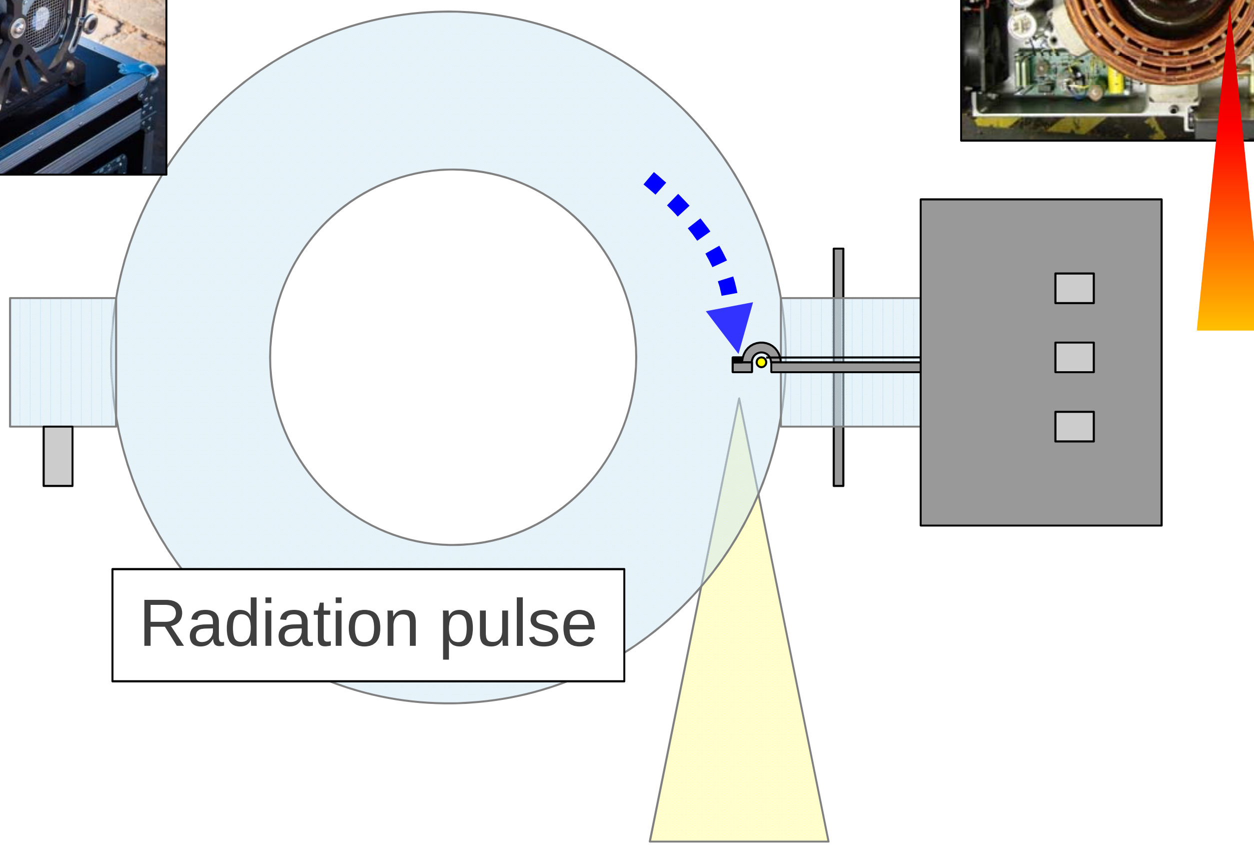
How Electrons Move (cont'd)



How it Works

How Electrons Move (cont'd)





Betatron Operation

- Electron injection from filament
- Contraction bunches electrons
- Expansion kicks electrons out of orbit to target

- Injector current and timing
- Contraction timing
- Expansion timing

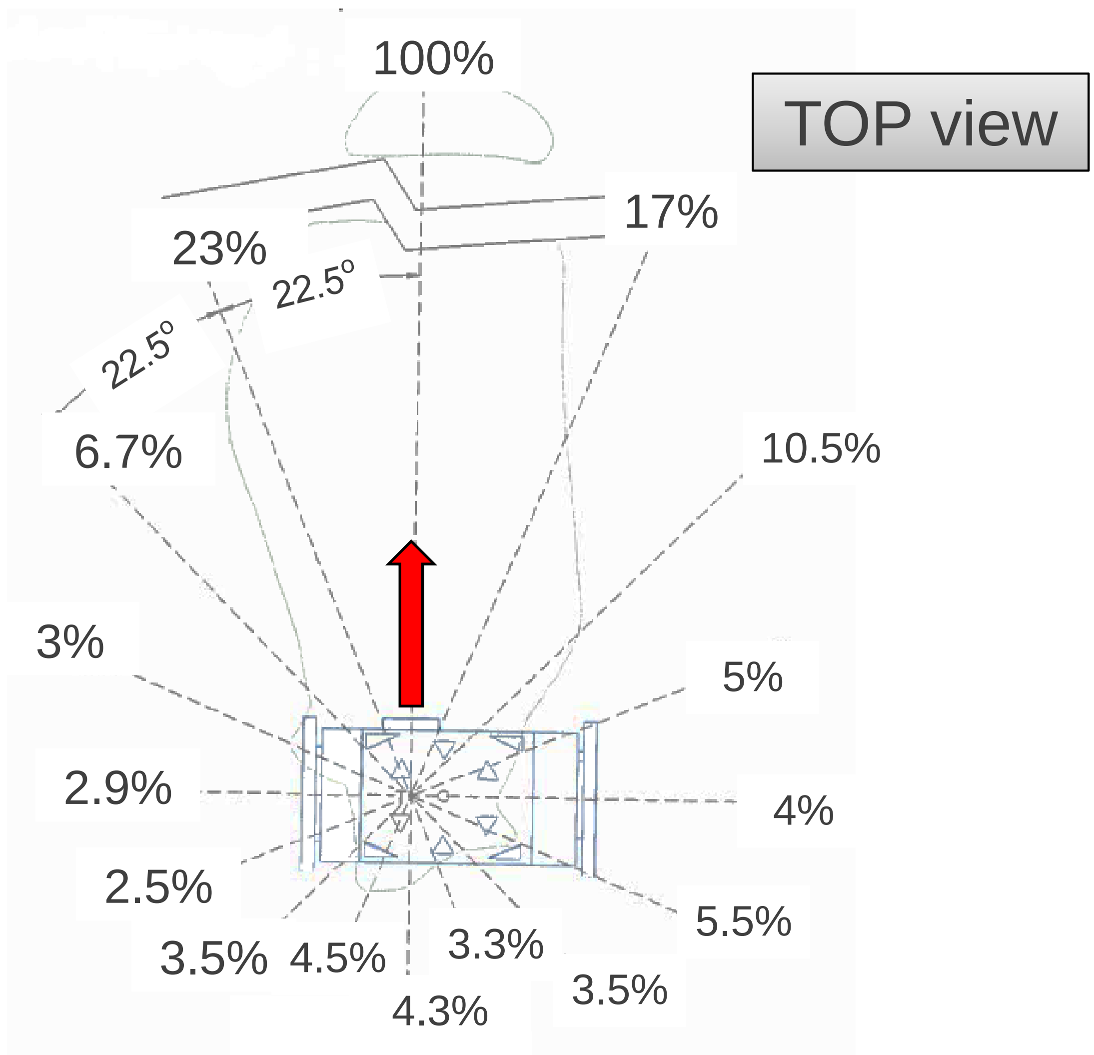
Points to Note

- Cycle repeats 200 times a second (for standard 6 and 7.5MeV systems)
- As such, radiation output is pulsed – not continuous!
- Radiation pulse duration is only 1-2 micro-seconds!

Typical Betatron Output

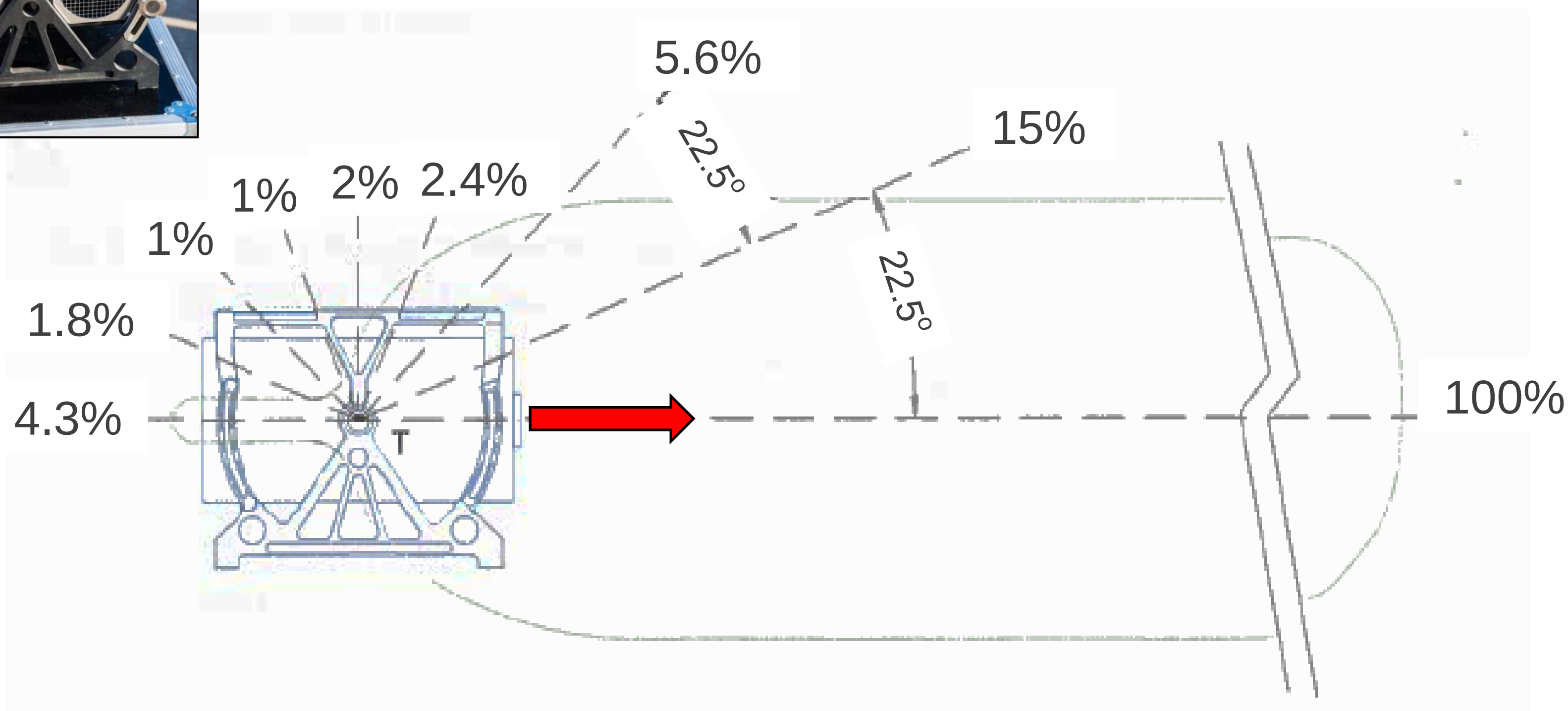
6 MeV:	**60 mGy/min @ 1 meter**	(6.0 R/min)
5 MeV:	**24 mGy/min @ 1 meter**	(2.4 R/min)
4 MeV:	**14 mGy/min @ 1 meter**	(1.4 R/min)
3 MeV:	**6 mGy/min @ 1 meter**	(0.6 R/min)
2 MeV:	**2 mGy/min @ 1 meter**	(0.2 R/min)

Radiation Pattern



Radiation Pattern (cont'd)

SIDE view



How to Operate the Betatron

Betatron Operation

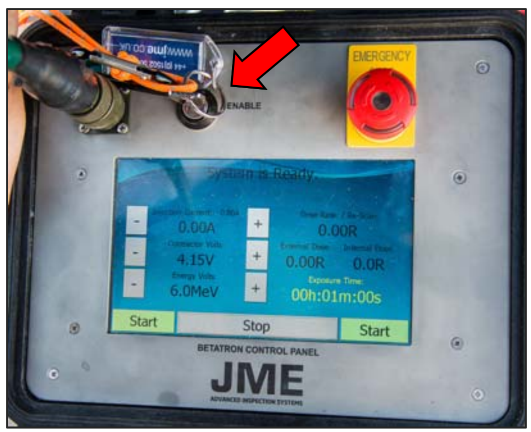
- Setup/precautions
- Cable connections
- Power up
- Key control

Setup/Precautions

- All operators (including maintenance personnel) should wear personal dosimeters
- Check pins and sockets of cables and outlets for damage
- Recommended: Allow all equipment to stabilize to ambient room temperature (above 15^{o}C)

Setup/Precautions (cont'd)

- **Ensure <u>both</u> keys are removed**
  - Power unit key
  - Control panel key
    - **MUST** be removed when unattended and after **EVERY** exposure



Setup/Precautions (cont'd)

- Ensure circuit breaker on Power Unit is set to OFF position

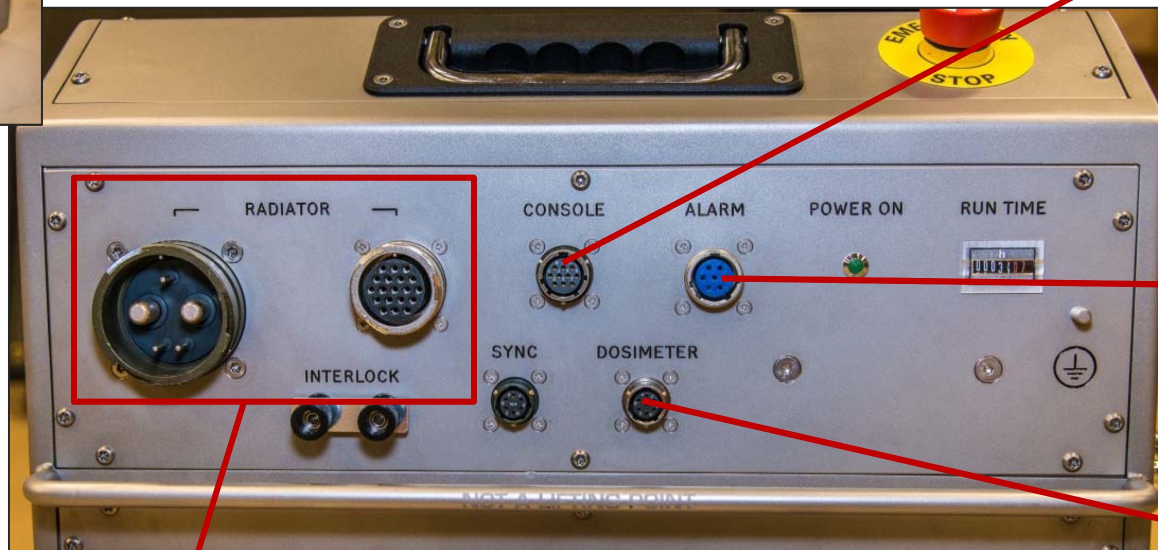
Circuit breaker

- Ensure the two Emergency Stop push buttons are in raised position (ON)

Emergency Stop buttons
in UP (ON) position

Connections

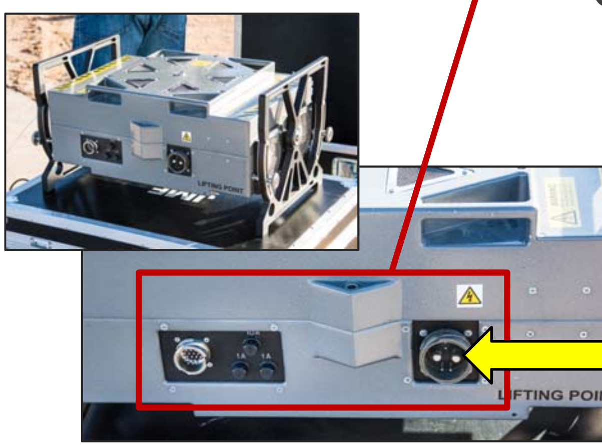
Control Panel



Alarm

Connector panel

Remote Dosimeter



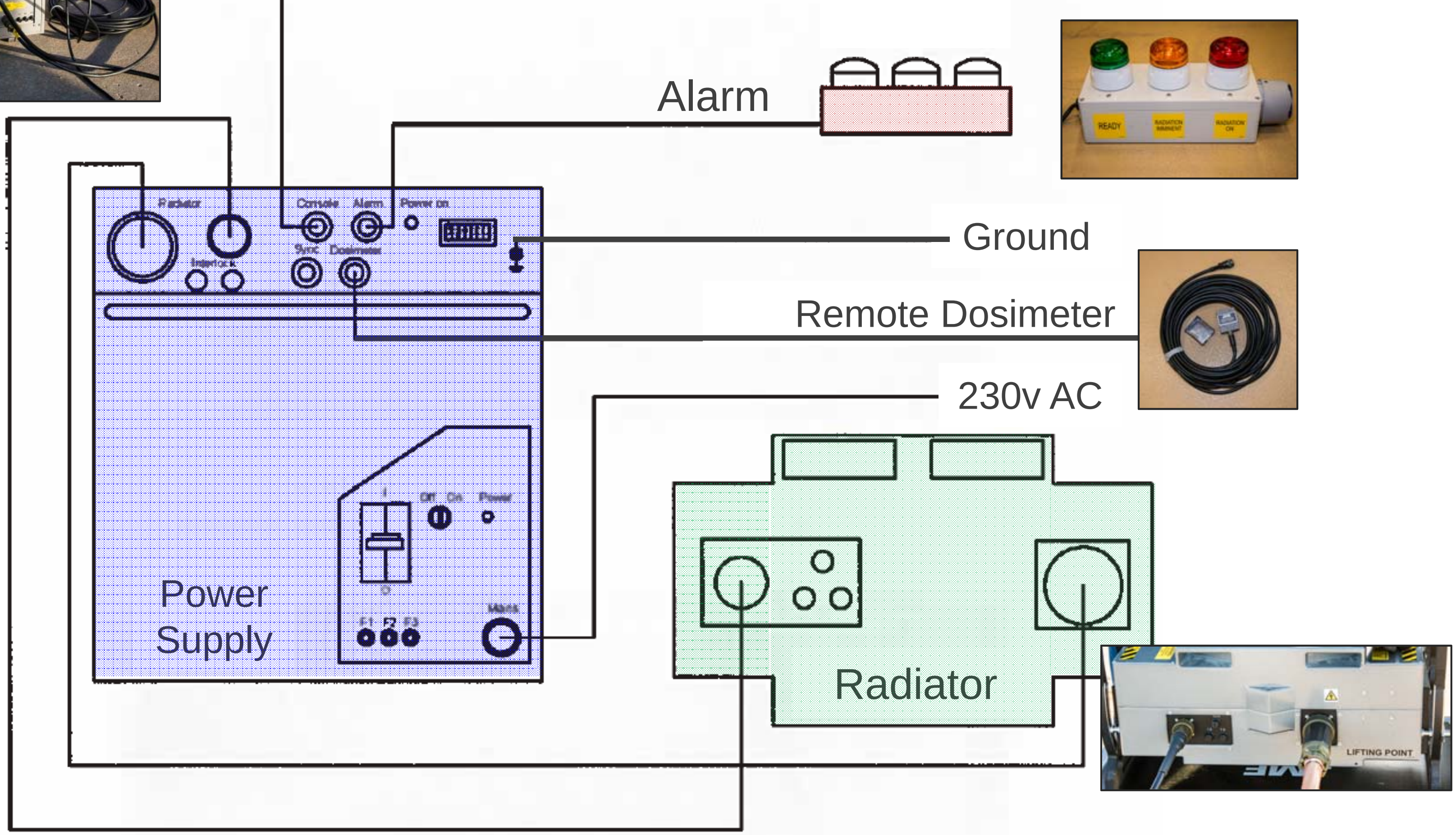
230v AC

Mains panel

Main control cable

Connections

Another View

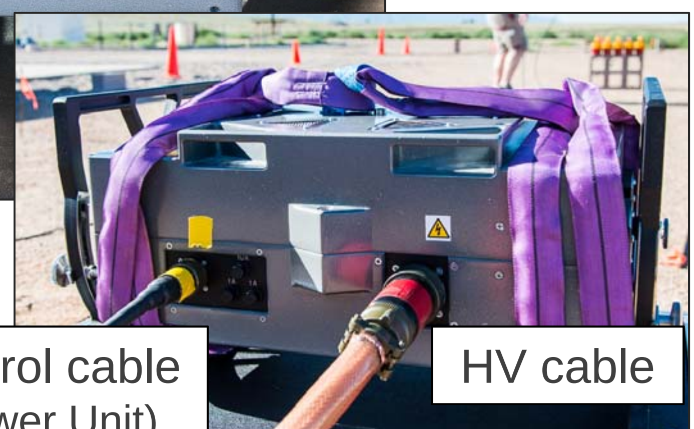


Connections

X-ray Radiator

High voltage
(HV) cable

- Fully uncoil HV cable
- Avoid crossing the 2 cables
  - If unavoidable, cross at 90°



Control cable
(Power Unit)

HV cable

Cables

- **High Voltage Cable**
  - Ensure it is fully uncoiled
  - Don't cross itself or other cables
  - Protect the connector ends
    - Avoid dropping on hard surfaces

Cables (cont'd)

Other Cables

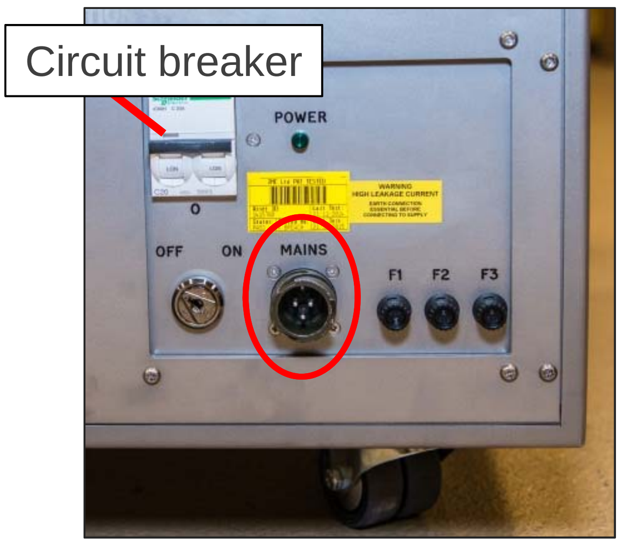
- Do not pull any of the modules by the cables
- Take care of connectors

Operating the Betatron

1. Connect all cables from Power Unit to external modules

Operating the Betatron (cont'd)

2. Connect mains cable from Power unit to suitable power supply
3. Switch ON Power Unit's circuit breaker

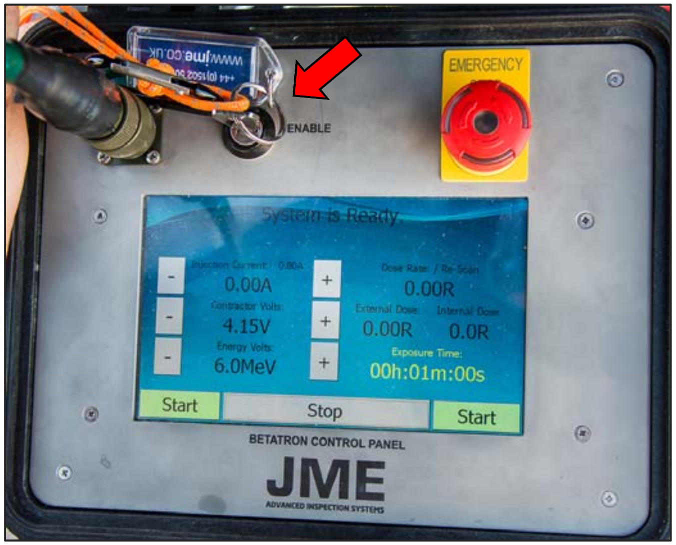


Operating the Betatron (cont'd)

4. Wait 3 – 4 seconds (after turning on circuit breaker) then turn main key switch ON

Operating the Betatron (cont'd)

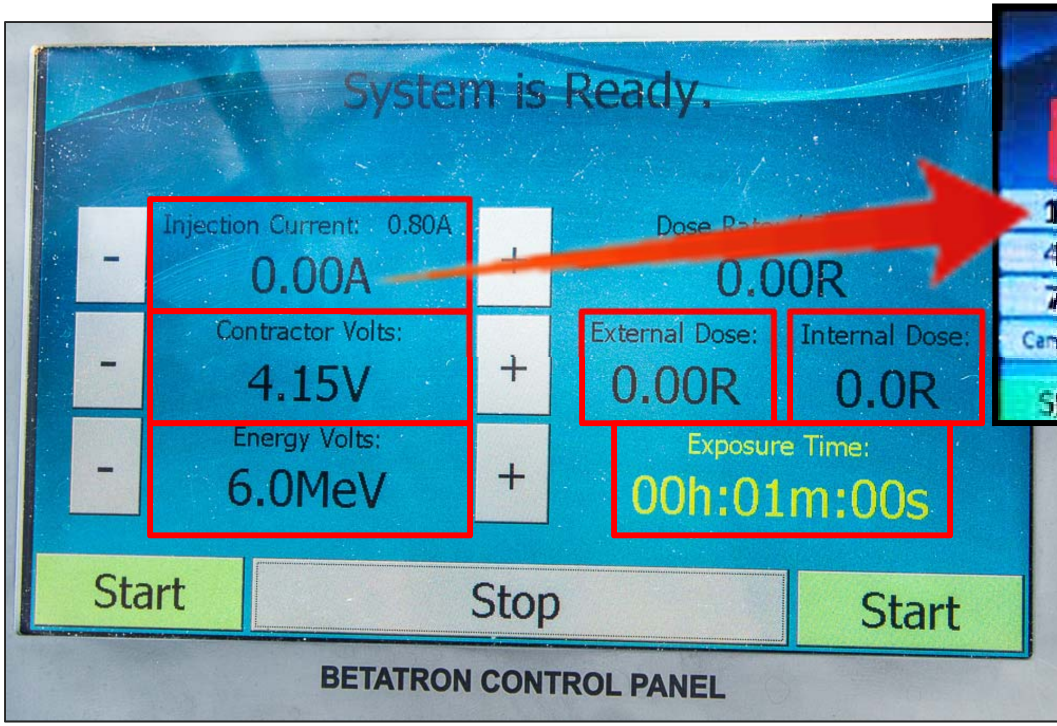
5. Turn key-switch on Control Panel to ON
   - Ensure no one is in radiation area of X-ray Radiator before turning on
   - Takes time to boot up
   - Power Unit's power indicator light turns on

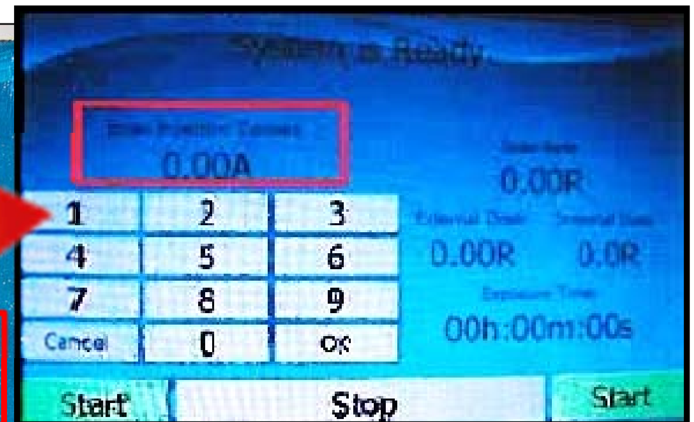


Operating the Control Panel

Operating the Control Panel

- Tapping on red boxed areas will open a new screen (Red boxes not actually on screen)

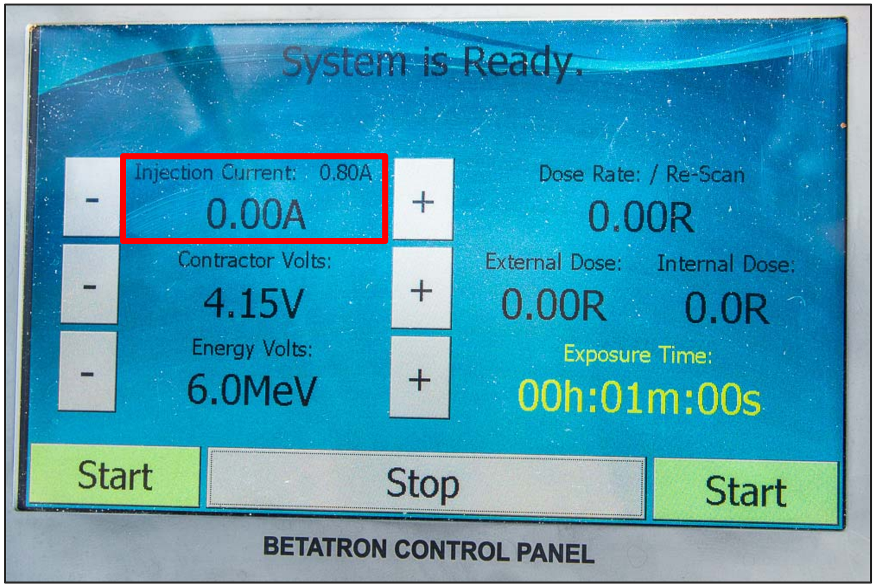




New screen – Input desired parameters

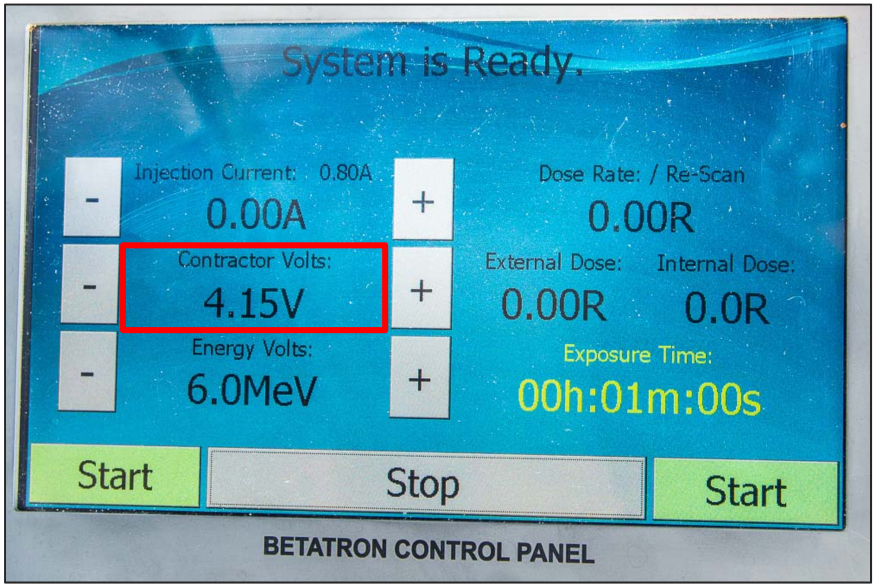
Injection Current Screen

- Should be set to value stated on tube certificate
- Minor adjustments can be made to optimize dose output
- Increase as tube ages
- May need to press “Dose Rate” to initiate a scan for optimal output



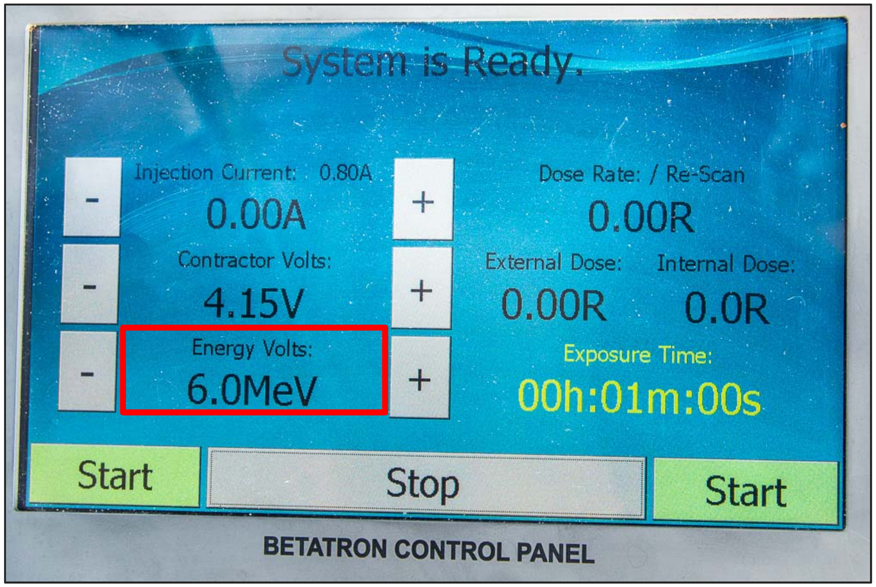
Contractor Voltage Screen

- Should be set to value stated on tube certificate
- Minor adjustments can be made to optimize dose output
- Adjust as system gets warmer/cooler
- May need to press “Dose Rate” to initiate a scan for optimal output



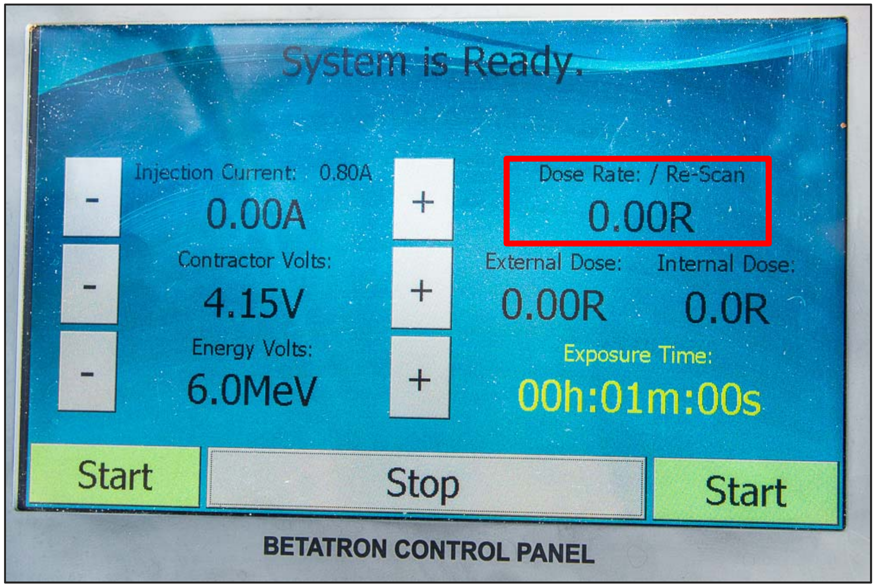
Energy Volts Screen

- Electron energy – X-ray spectrum endpoint
- 2.0 to 6.0 MeV range in 0.1 MeV increments
- May need to press “Dose Rate” to initiate a scan for optimal output



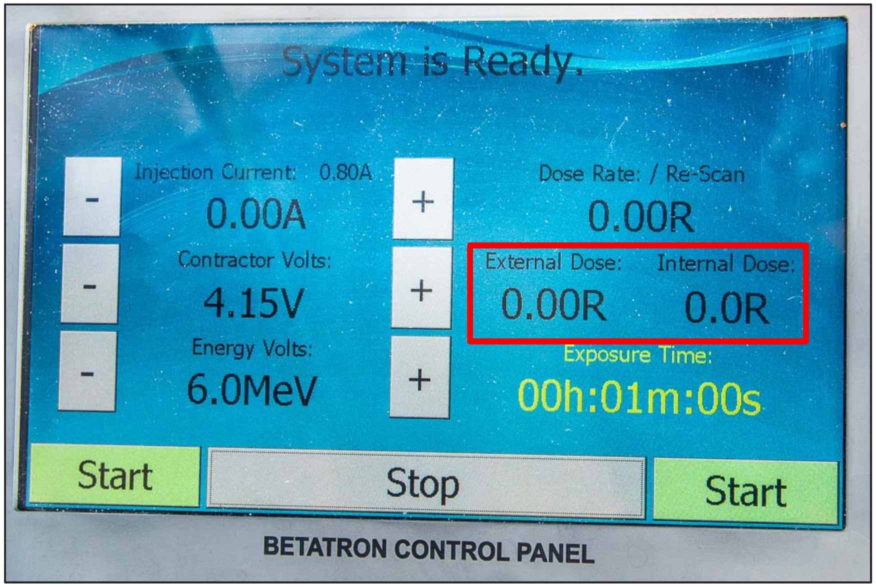
Dose Rate Optimization Scan

- Tapping “Dose Rate” initiates a scan to optimize dose rate



Exposure Control by Dose

- Enter desired dose
- **External Dose** – uses external dosimeter OR
- **Internal Dose** – uses internal dosimeter
  - Measures total dose at one meter

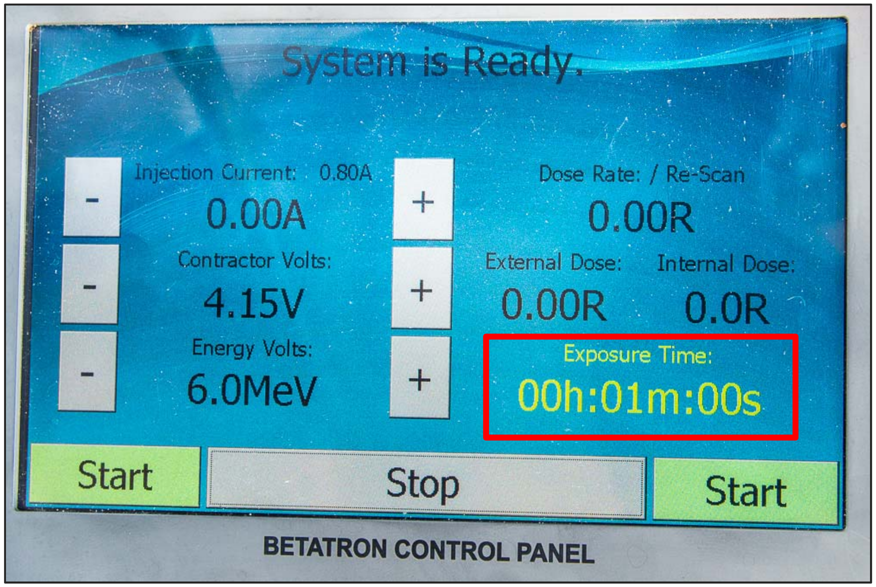


Exposure Control by Dose (cont'd)

- **External Dose**
  - Measures dose where dosimeter is put
  - If put behind part, measures dose to image plate
  - If internal material of IPC is unknown, dose may be incorrect
- **Internal Dose – uses internal dosimeter**
  - Measures total dose at one meter
  - Must calculate dose at part (inverse square law)
  - Must account for part attenuation (half value layers)

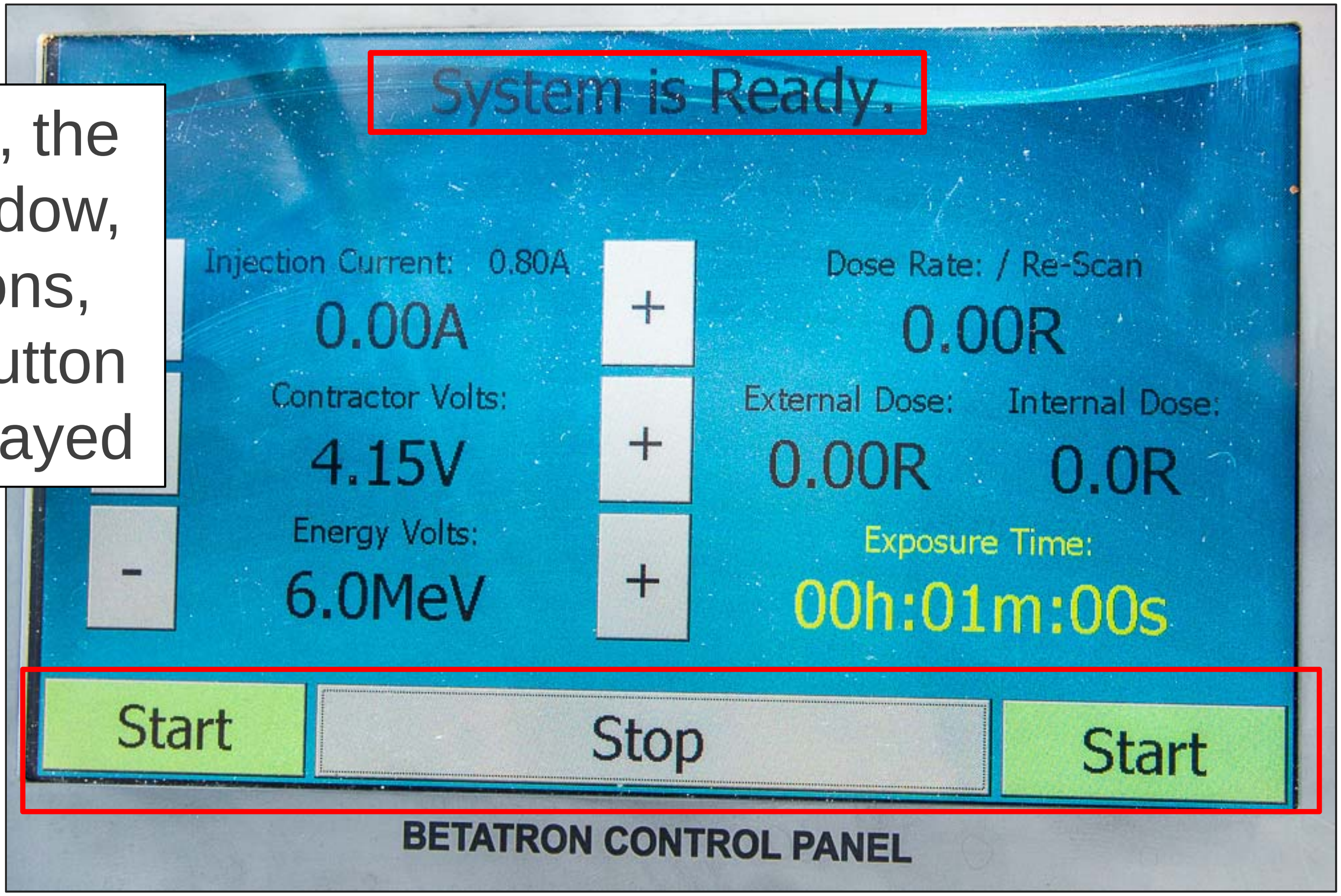
Exposure Control by Time

- Can control exposure by time
- Assumes a steady output



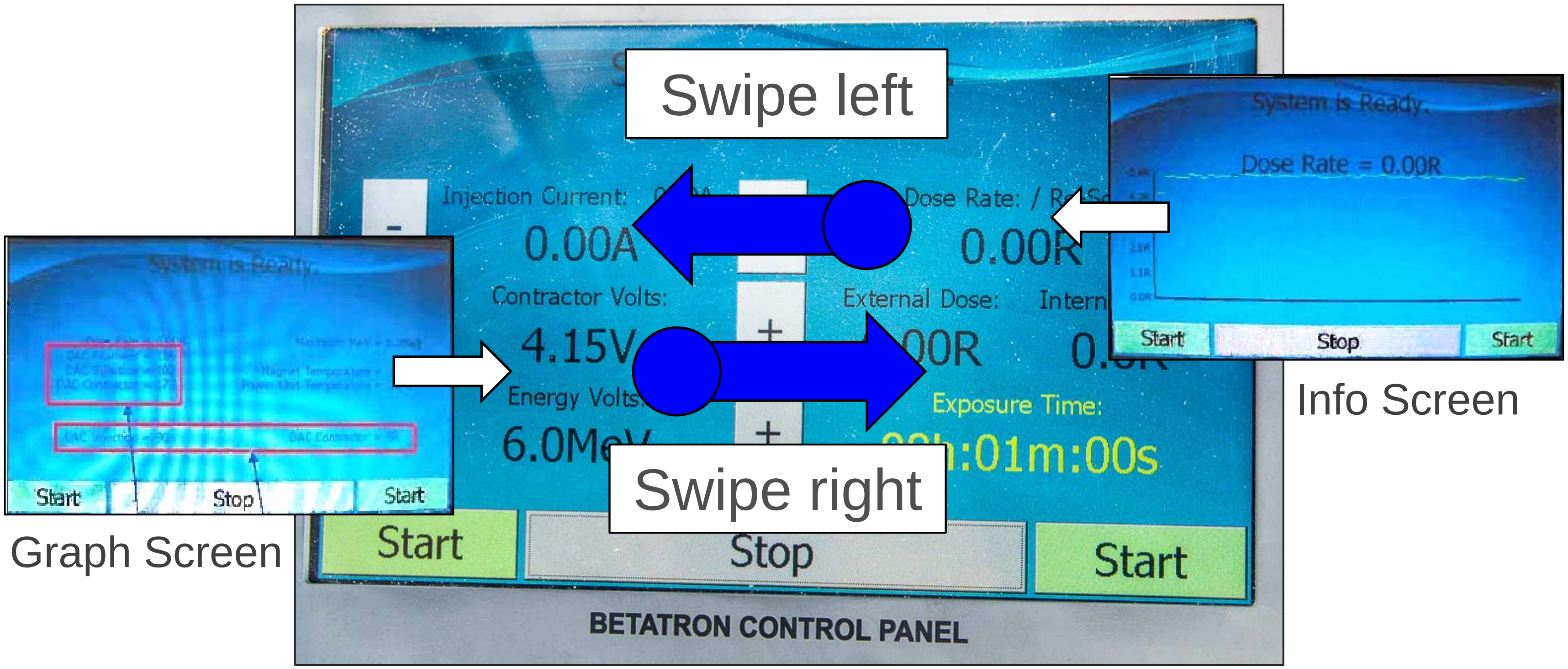
Status

At all times, the Status Window, Start buttons, and Stop button will be displayed



Information & Graph Screens

Press and Swipe Left or Right

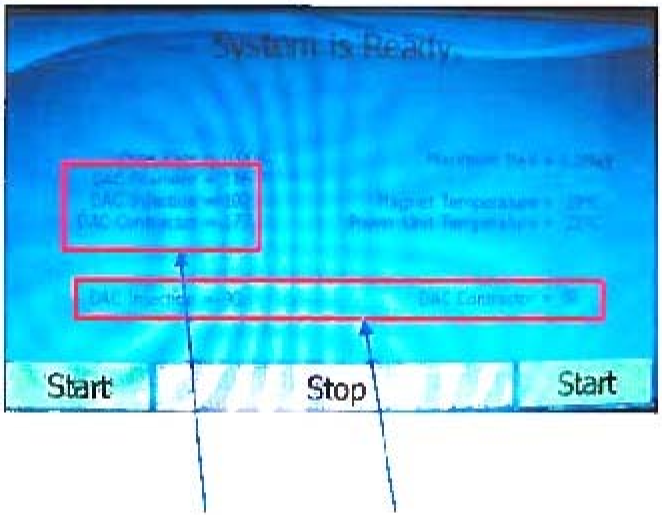


Information Screen

Press and Swipe Right

Screen displays

- Power unit temperature
- Magnet temperature
- DAC 1 Injection and Contractor Values
- DAC 2 Injection and Contractor Values



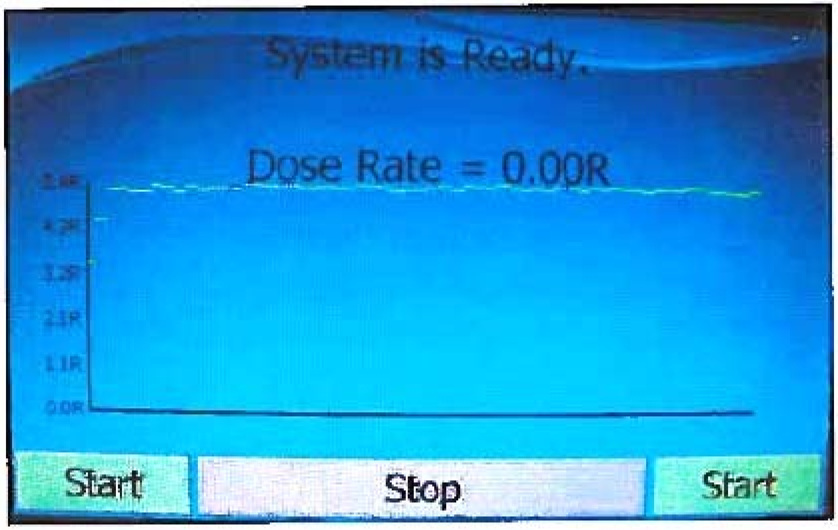
DAC (1) DAC (2)

- DAC values are between 0 – 255
- Between 50 and 200 is OK
- ***Lower than 50 or over 200 means internal adjustments are needed***

Information Screen (cont'd)

Press and Swipe Left

Temporary record of output dose rate



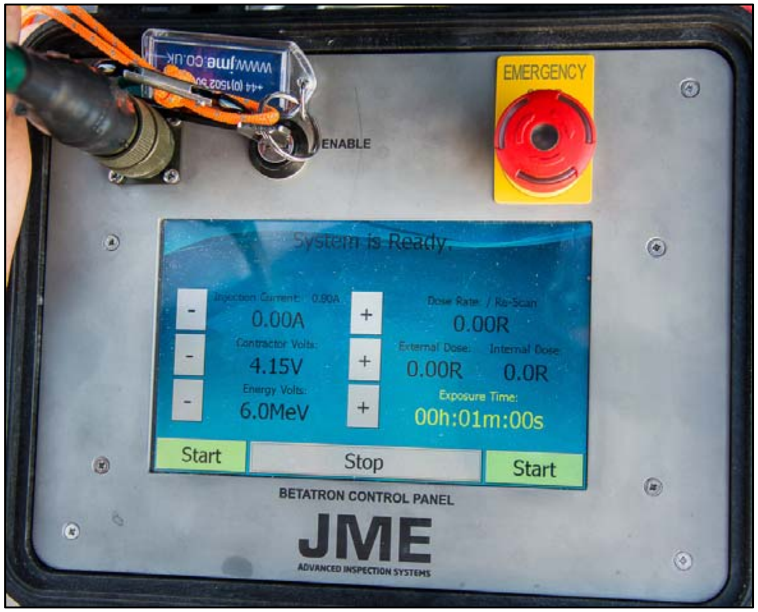
Activating the X-ray Radiator

Start/Stop X-rays

Insert Key

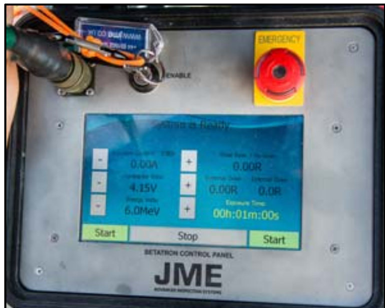
Safety

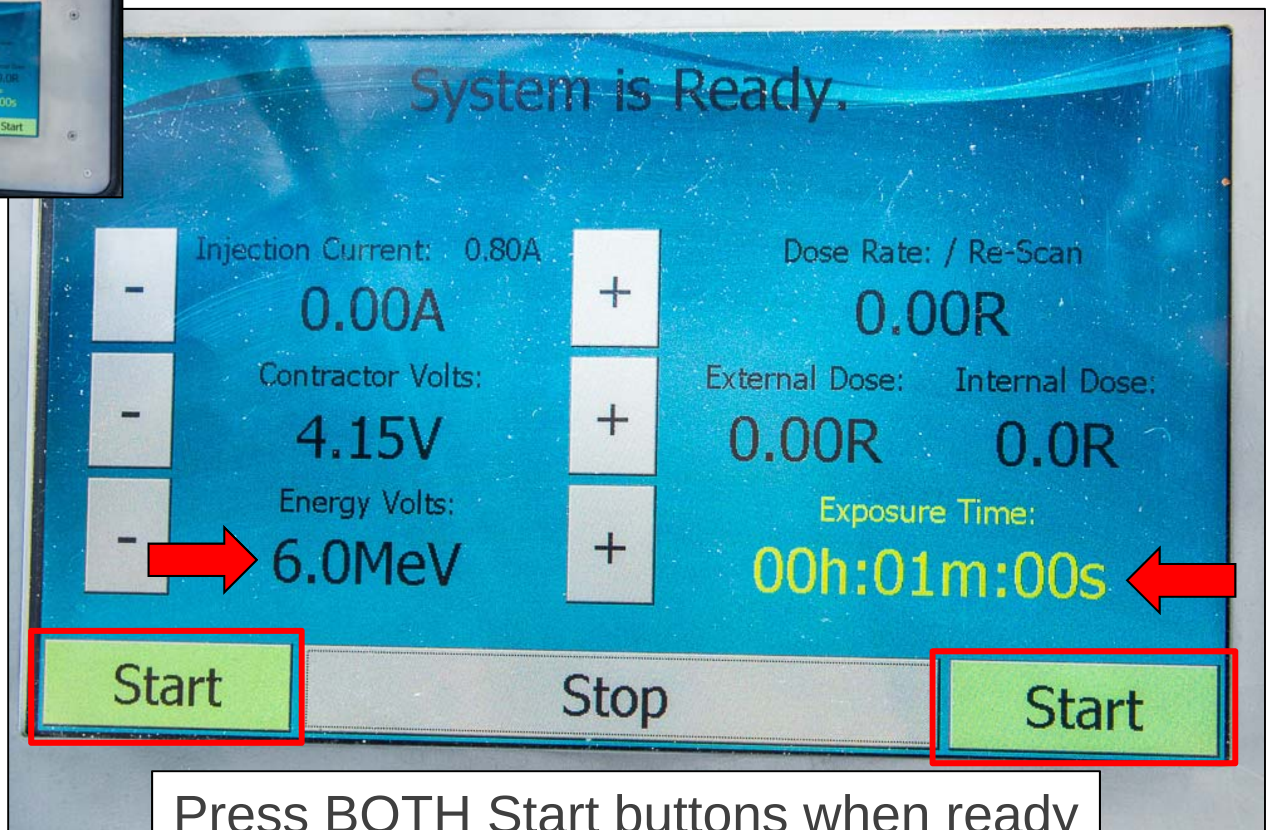
- Operate Control Panel in a radiation safe area
- Insert key once x-ray area is cleared of personnel



Start/Stop X-rays

Set Parameters



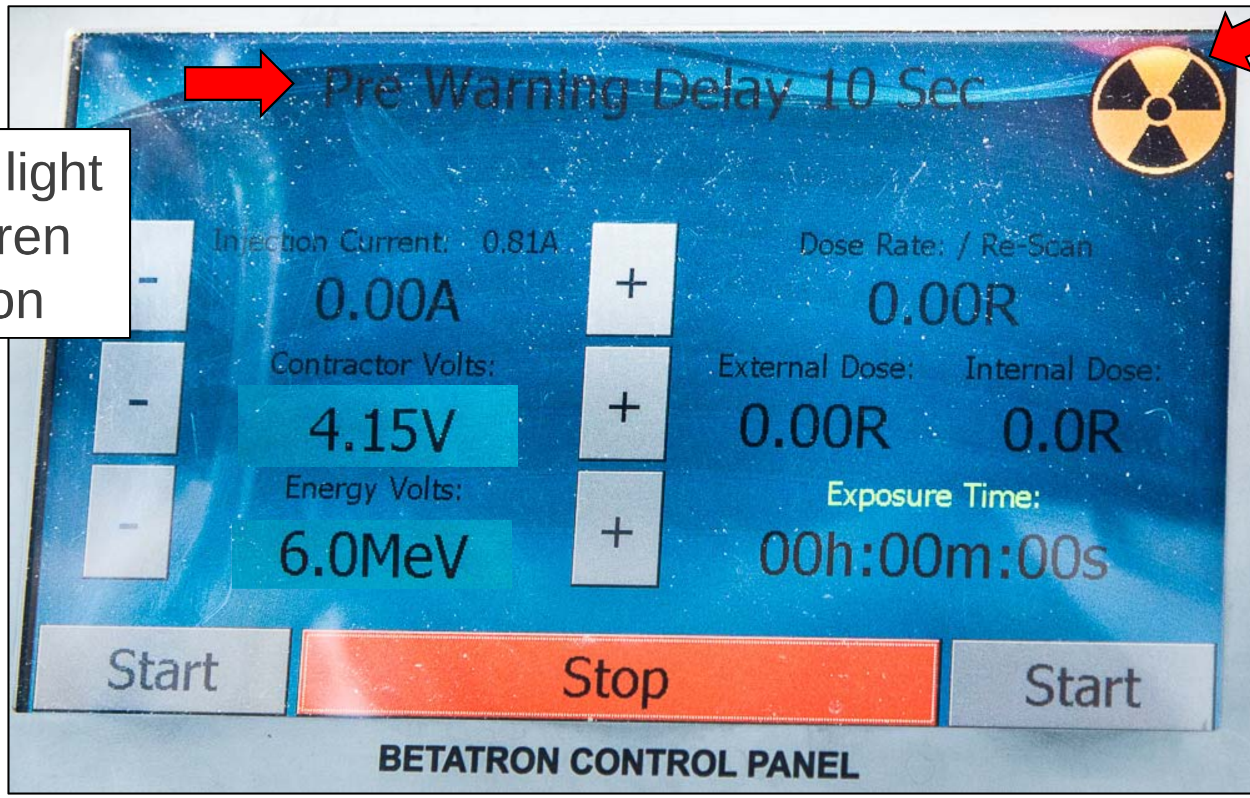


Press BOTH Start buttons when ready

Start/Stop X-rays

Pre Warning Delay – 10 sec

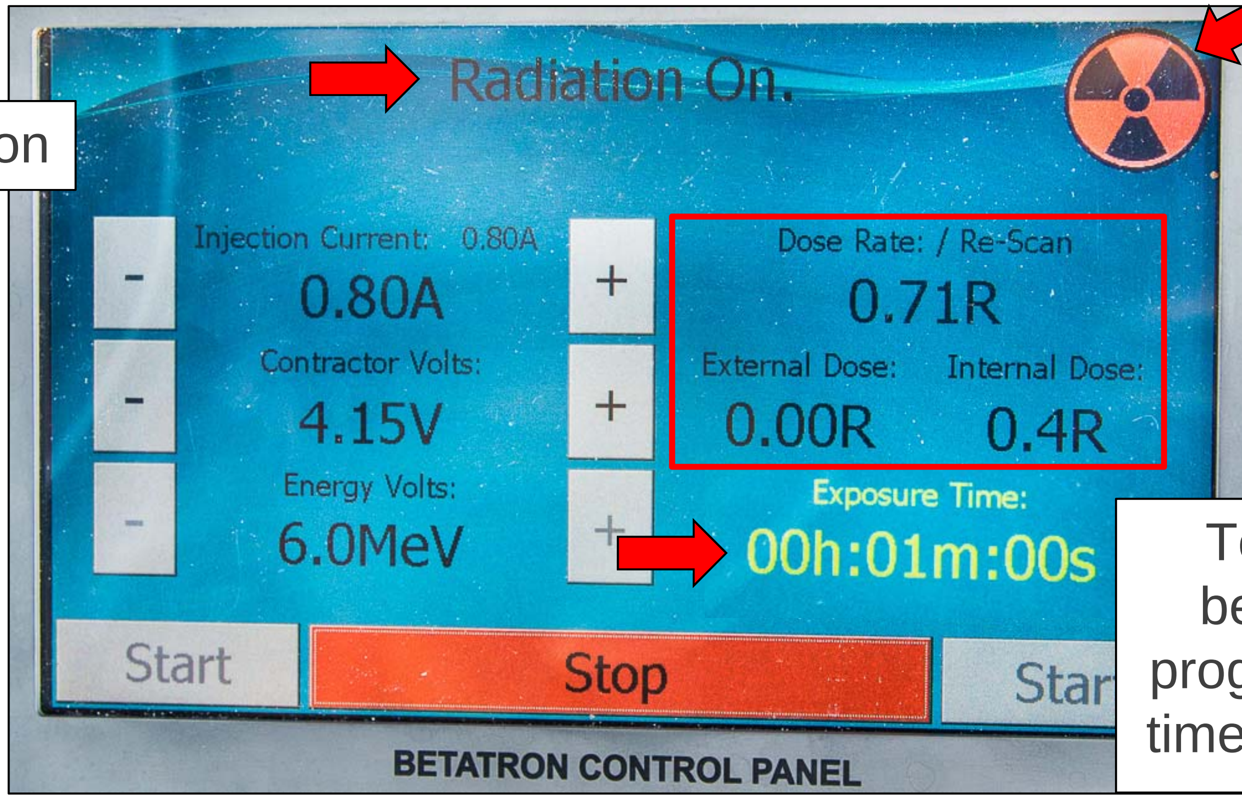
Amber light and siren turn on



Start/Stop X-rays

Radiation ON

Red light on

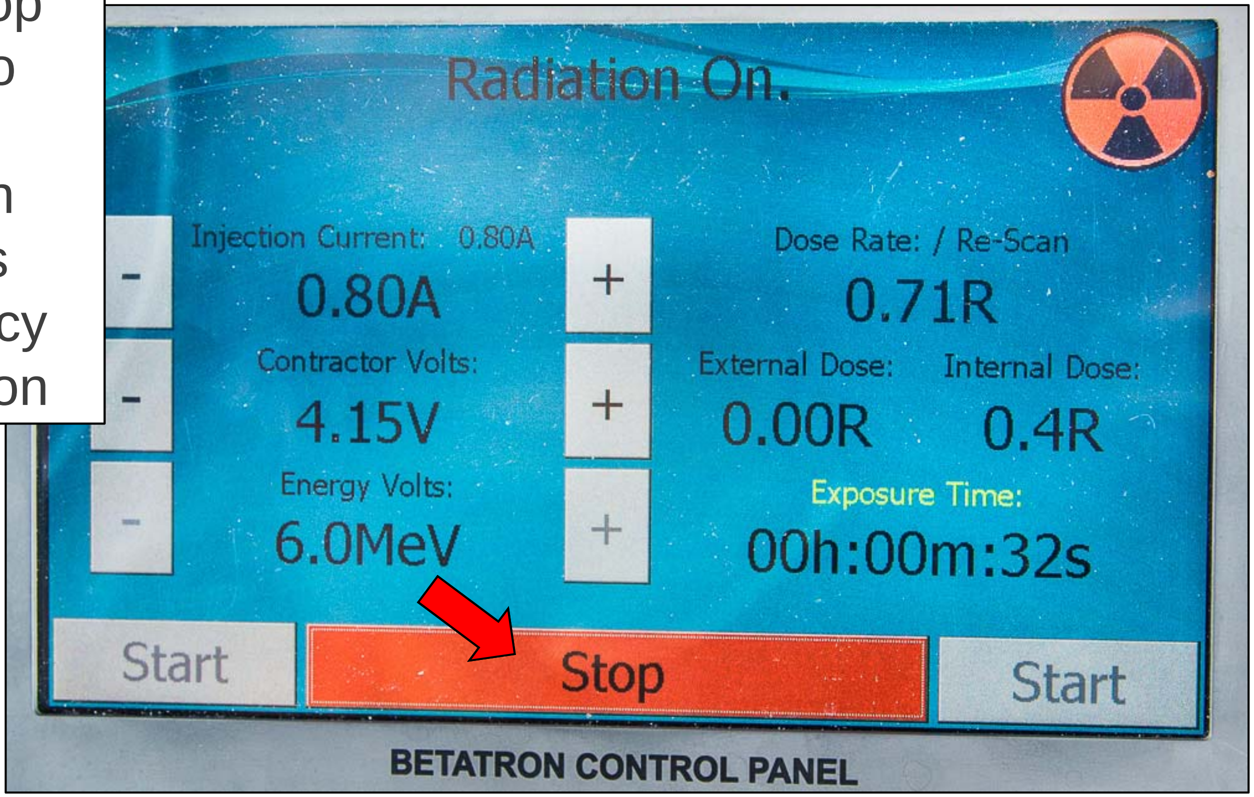


Toggles between programmed time & actual

Start/Stop X-rays

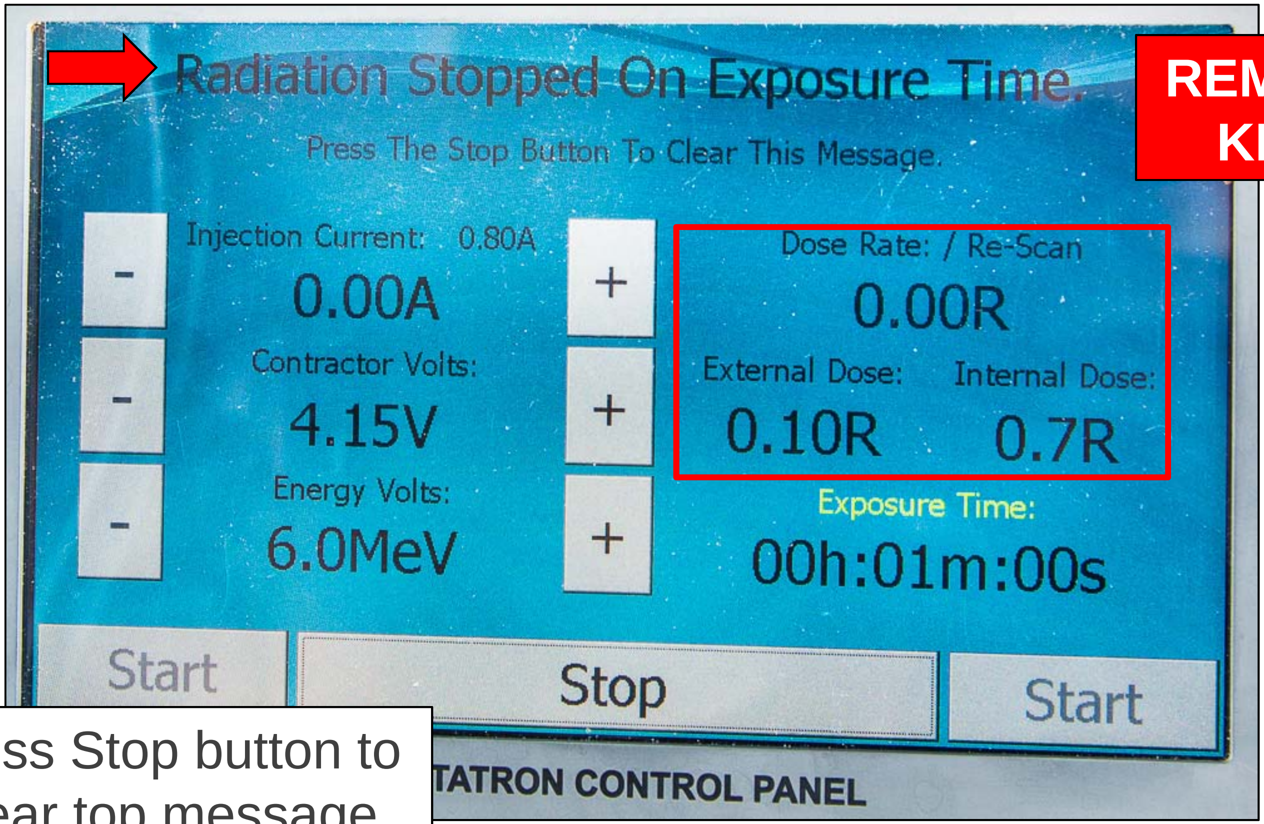
Radiation ON (cont'd)

Press Stop button to STOP radiation or press Emergency Stop button



Start/Stop X-rays

Radiation OFF



REMOVE KEY!

Press Stop button to clear top message

When Not Generating X-rays

- **ALWAYS** remove and secure the ENABLE key after each exposure!
- For short periods of time leave system on so that cooling fans operate
- For longer periods (>1 hour) turn power off

Lesson Summary

- **Betatron produces energies from 2.0 MeV to 6 MeV**
  - Output at 1 meter
    - 6 MeV = 60 mGy (6.0 R/min)
    - 4 MeV = 14 mGy (1.4 R/min)
    - 2 MeV = 2 mGy (0.2 R/min)
- **Electrical hazards are lethal – Do NOT open any of the equipment**
  - Some cables carry dangerous voltages
- **Protect from rain and snow**
- **Fully uncoil HV cable and keep away from other cables**

Lesson Summary (cont'd)

- **Remove Laser Alignment Unit from X-ray Radiator before taking x-ray**
- **Two keys are required to operate**
  - Turn on Power Unit first
  - Turn on Control Panel only when all personnel are clear of x-ray area
  - Remove Control Panel key ***after each exposure***
  - Wait 3 – 4 seconds (after turning on circuit breaker) before turning Power Unit main key switch ON

Practical matters…

Getting hands on with the system

Radiation Safety Procedures

ER-610-003
Personnel Health & Safety During Field Radiography Operations

Used for dozens of operations: Sandia; TTR; NNSS; ARG FFX domestic and international; LANL Remote Sites; US military bases

- Access Control & Personnel Accountability
- Dosimetry
- Postings
- Communications
- Coordination and Notifications with non-LANL organizations (MOUs)
- Regulatory requirements
- Special Work Permits (such as RWP)
- Key Control
- Documentation (Ops Log, Checklist, Accountability Log, Pre Job Briefing)

Betatron Course

Lesson 4

X-ray Energy, Contrast, Collimation and Filtering

Lesson Objectives

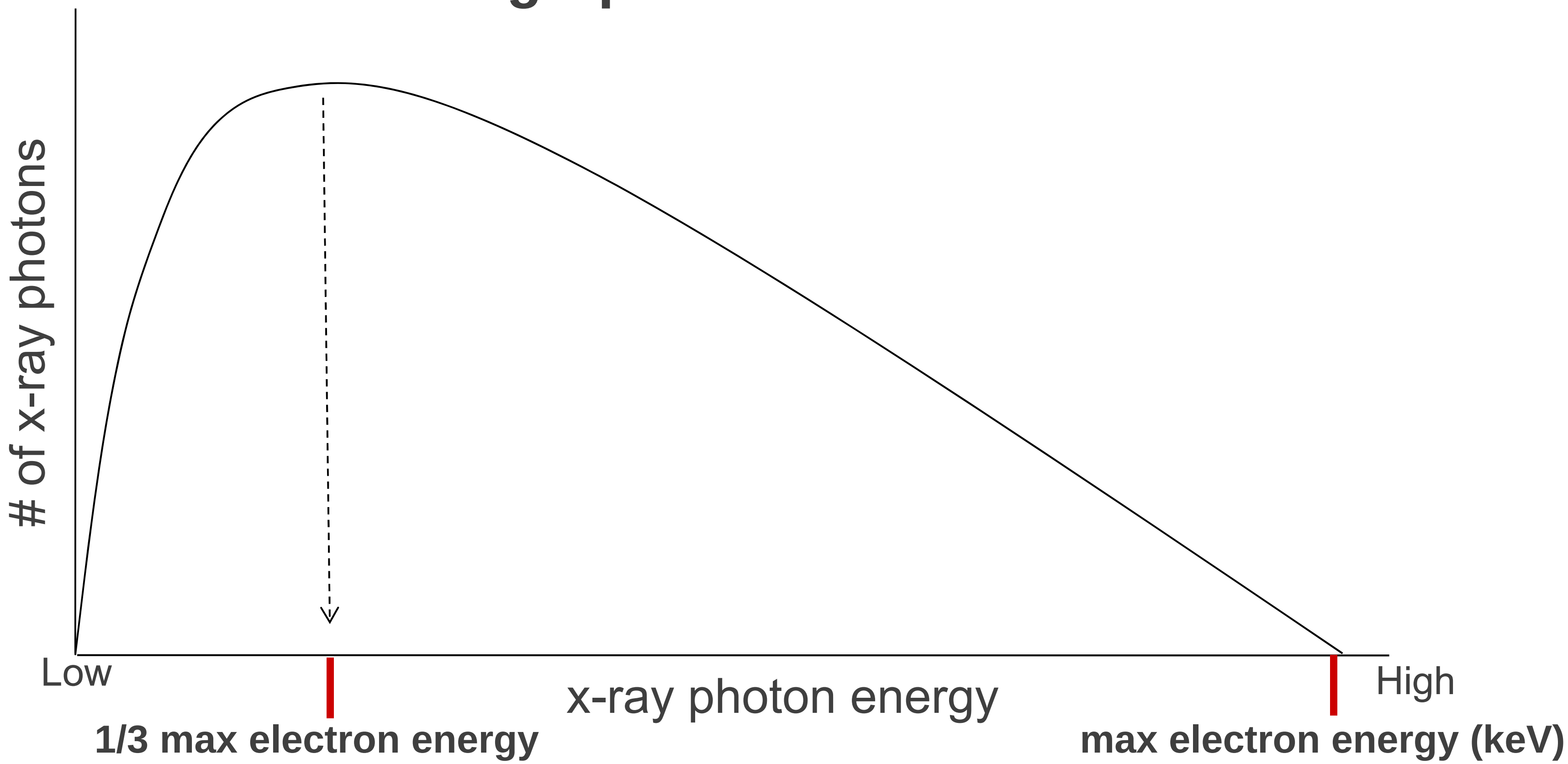
- Identify **factors that affect contrast** in an x-ray image
- Identify **techniques to increase contrast** in an x-ray image

Main Ideas

- **Contrast is the information in the image**
- **X-ray energy affects contrast**
- **Scatter affects contrast negatively**
  - Obscures the image
  - Try to reduce scatter
- **Size of feature and its contrast define the ability to detect the feature**

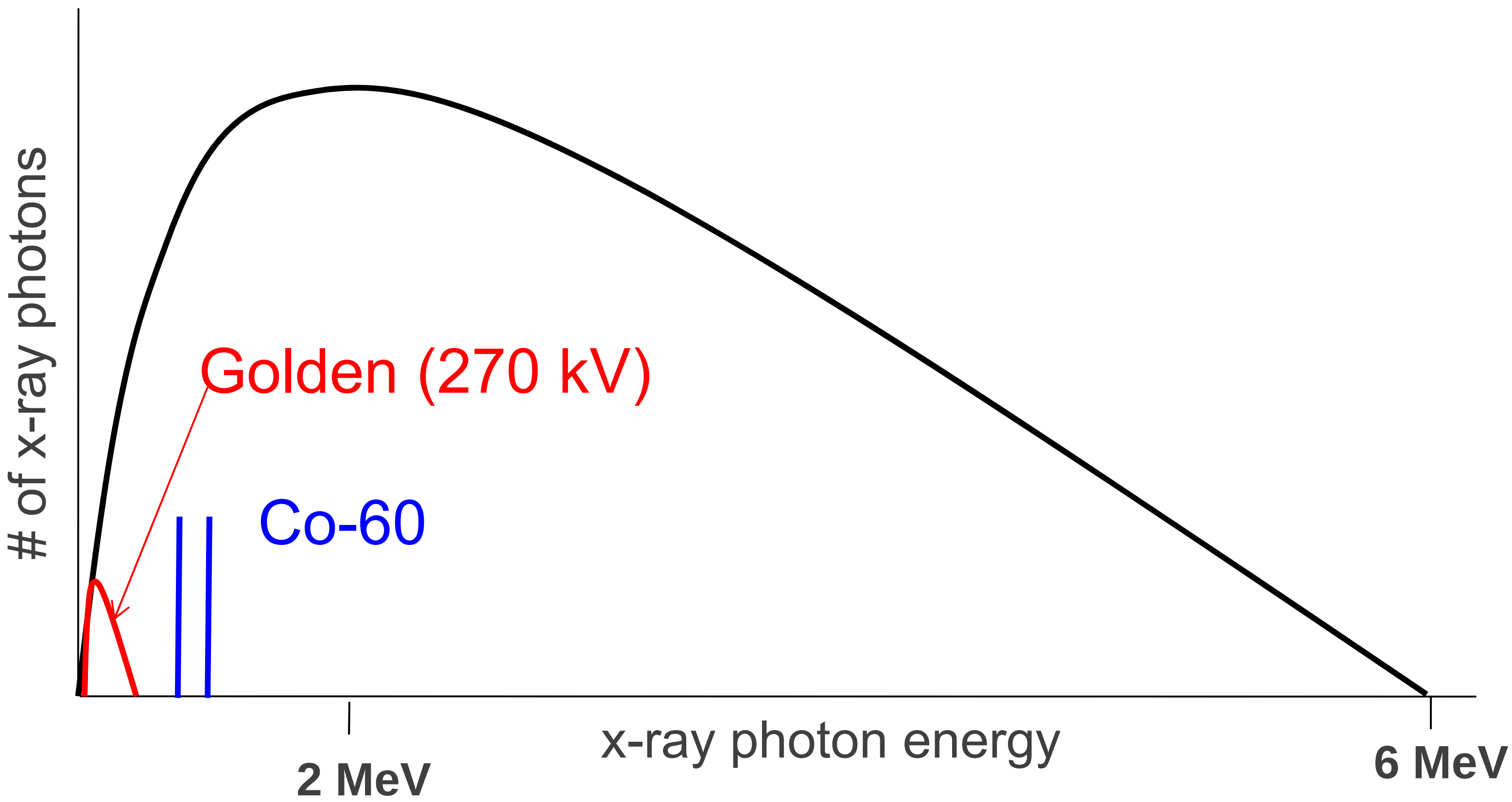
X-ray Energy

- **Bremsstrahlung Spectrum**



X-ray Spectrum

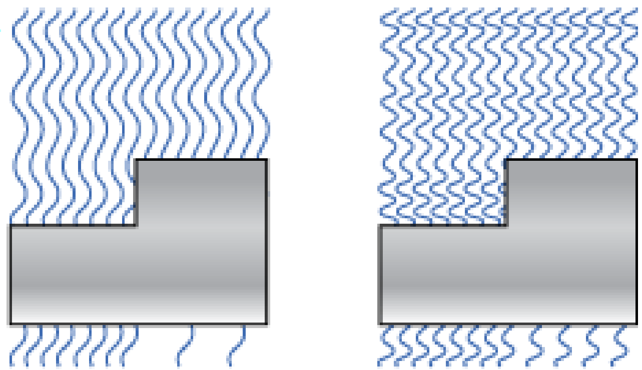
- **Bremsstrahlung Spectrum (6 MeV)**



Energy and Contrast

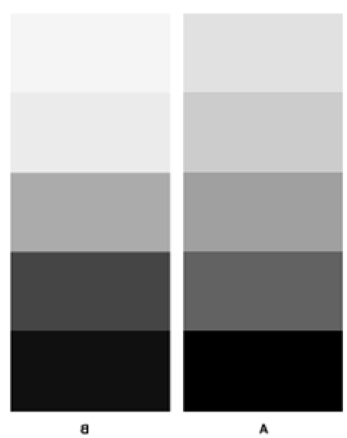
Low keV

High keV



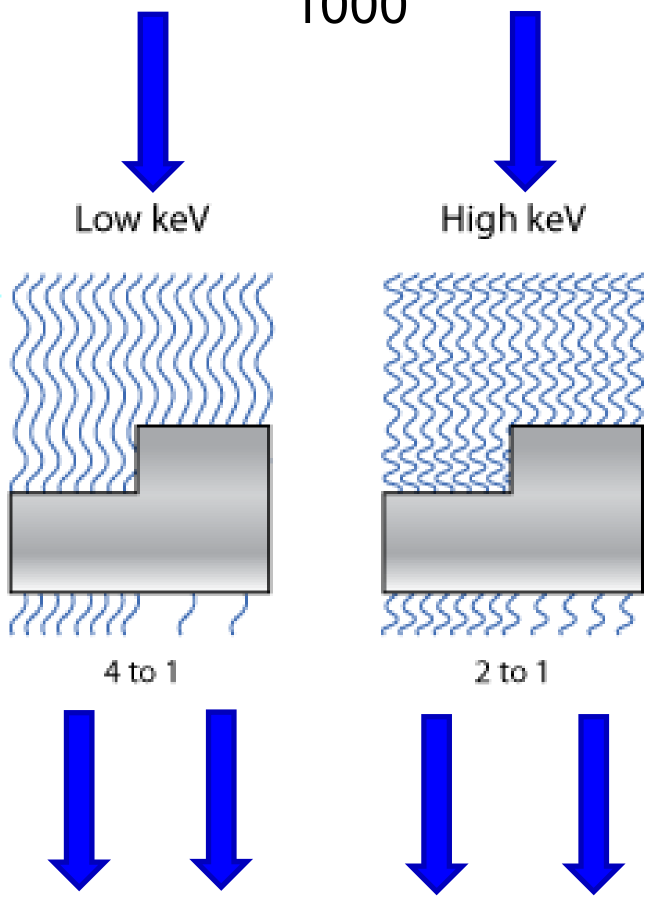
4 to 1

2 to 1



Contrast

1000



Contrast = 100/25

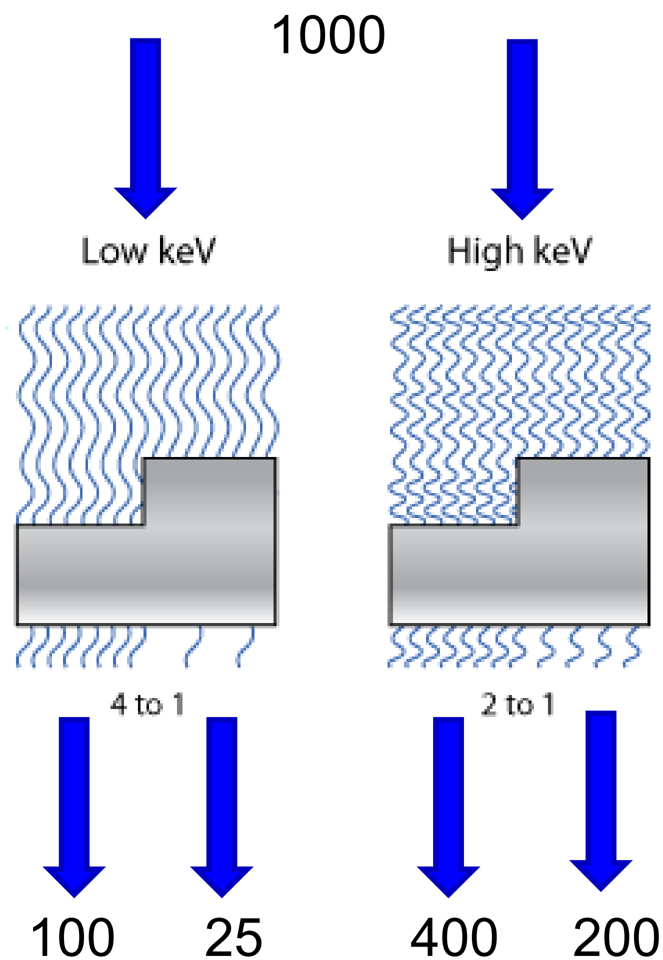
Contrast = 400/200

100 25 400 200

Contrast (cont'd)

Depends on

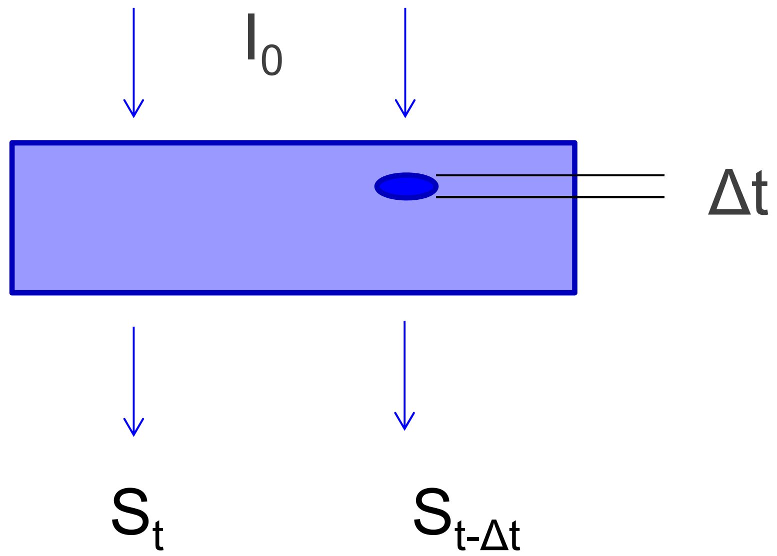
- Part thickness difference
- X-ray Energy
- Material (Z and density)



Contrast = 100/25

Contrast = 400/200

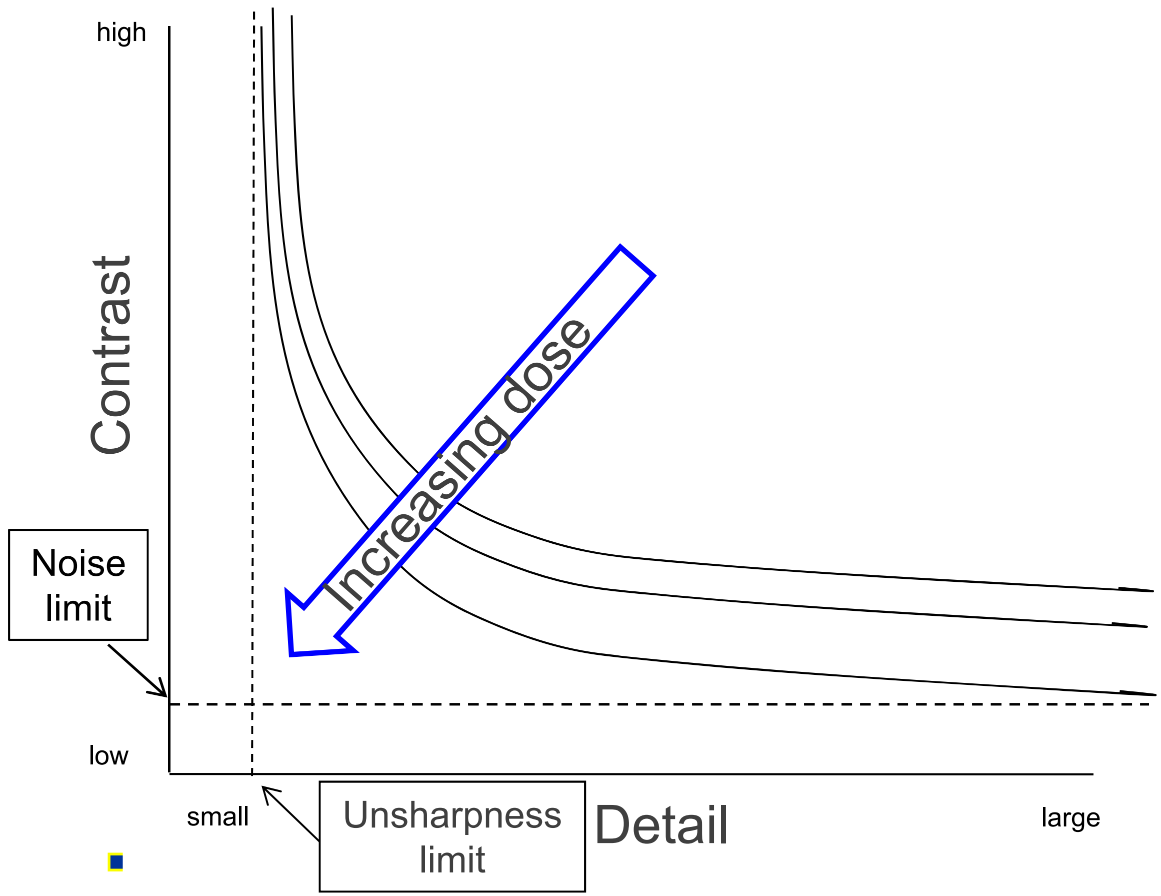
Contrast (cont'd)



Contrast = $S_{t-\Delta t}$ - S_t

Contrast-Detail-Dose

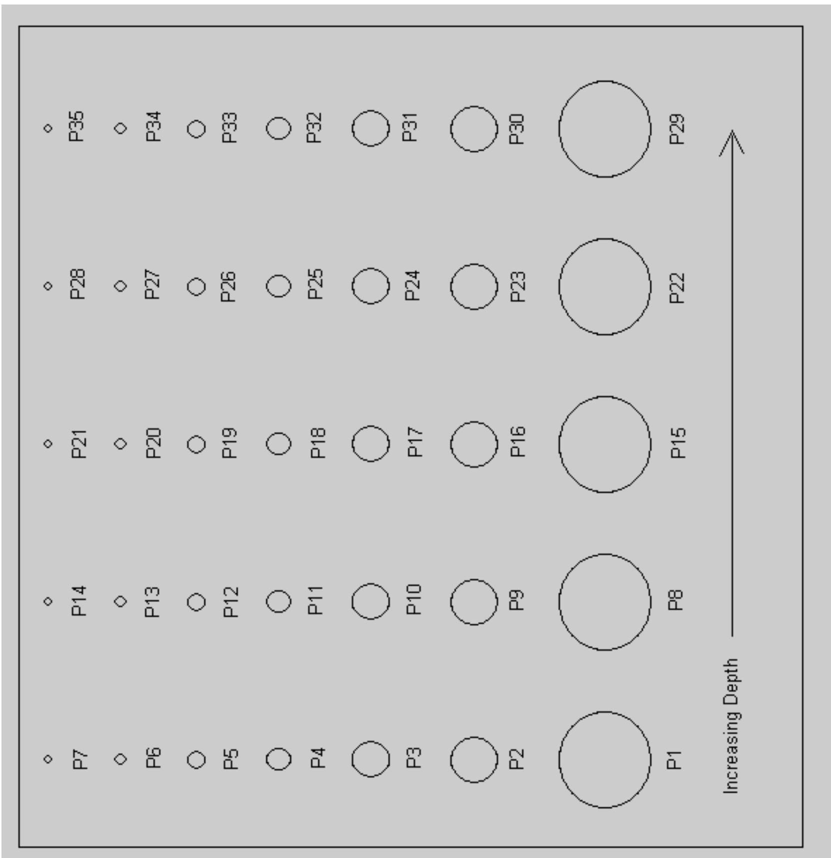
All imaging systems can be characterized by CDD curves

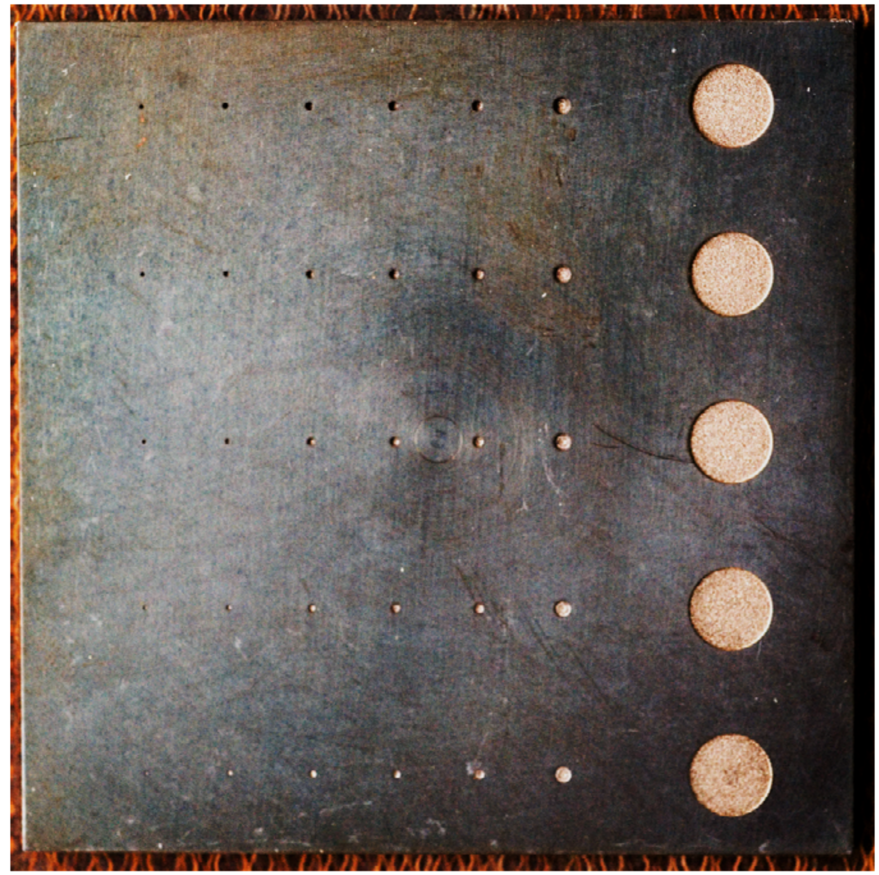


Increasing Dose

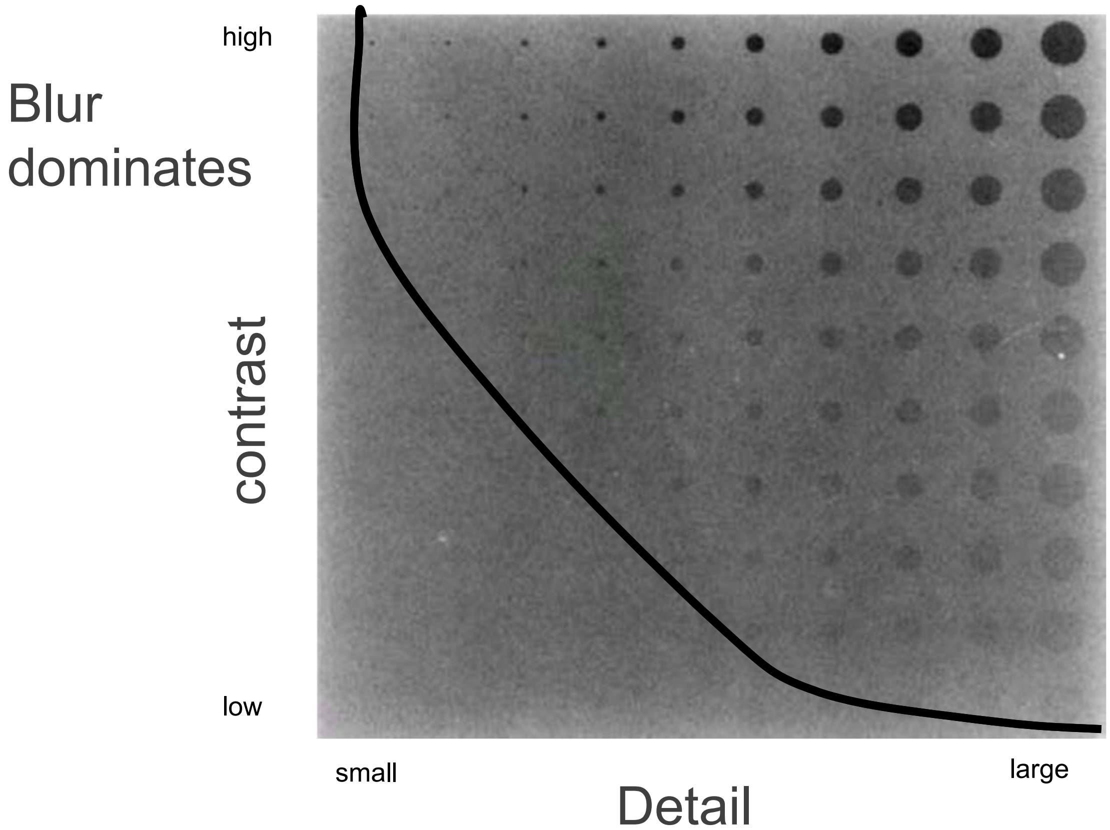
- Increases signal to noise
- Increases contrast to noise
- Increases ability to detect visually

Hole Phantom





Phantom Contrast-Detail

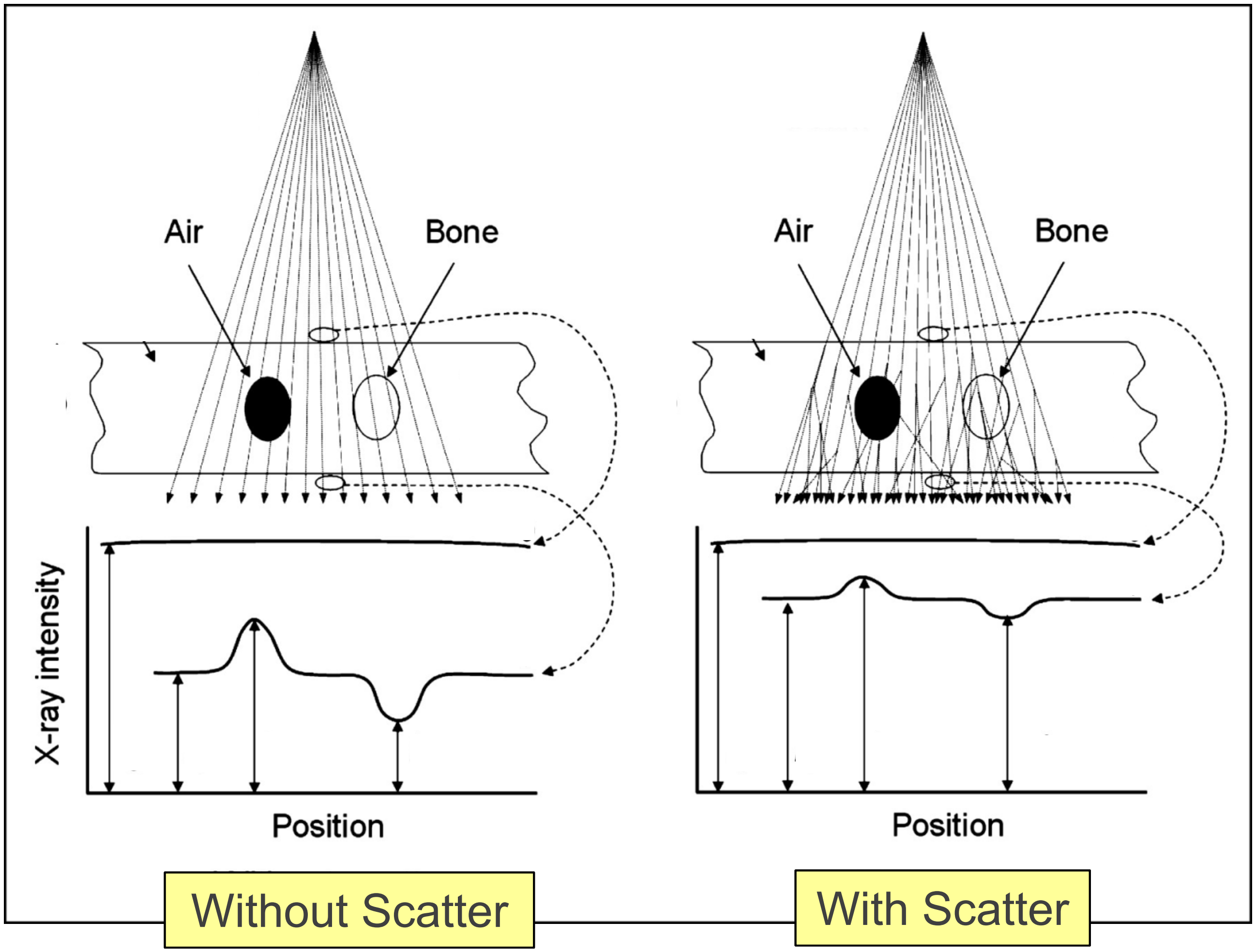


Effect of Noise and Blur

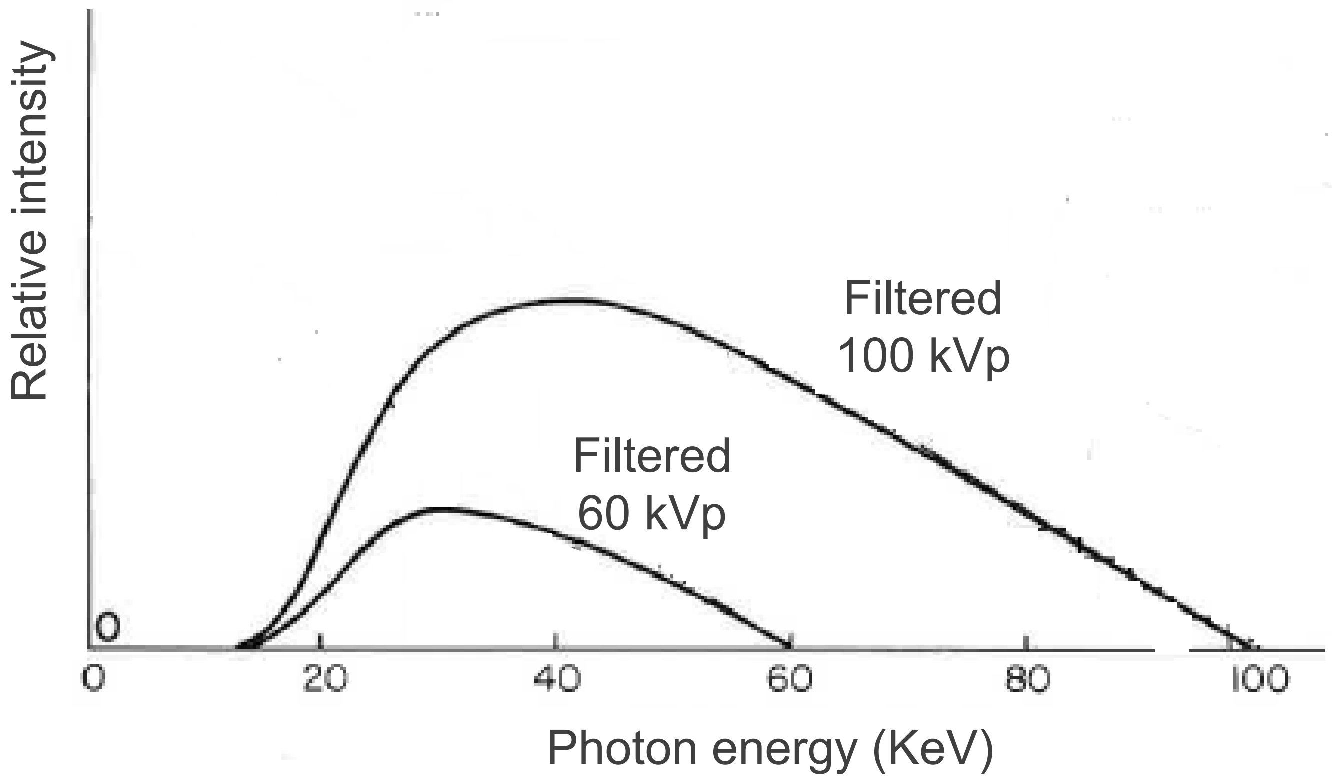
Scatter

- What is scatter and why is it bad?
- Part scatter
- Floor scatter
- Backscatter
- Detector scatter

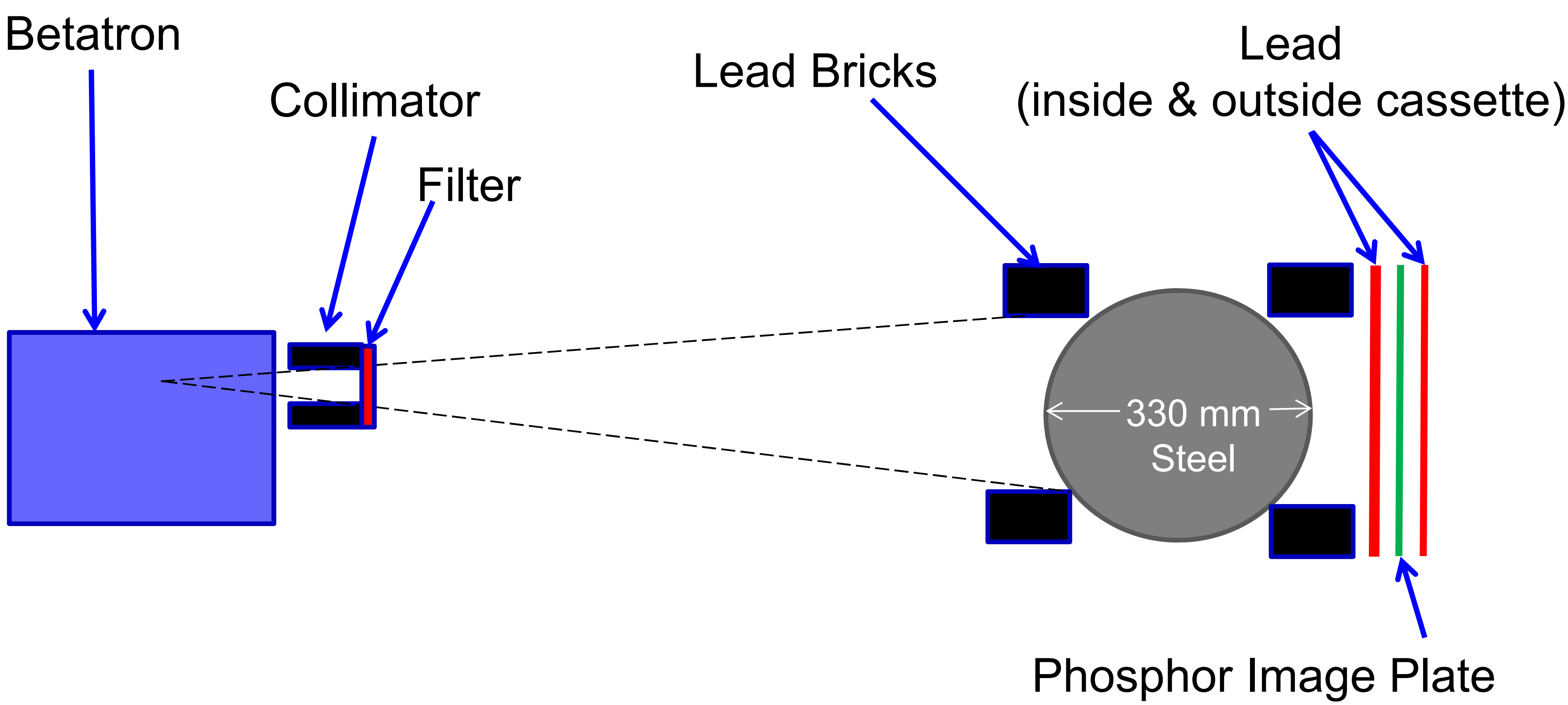
Scatter Degrades Contrast



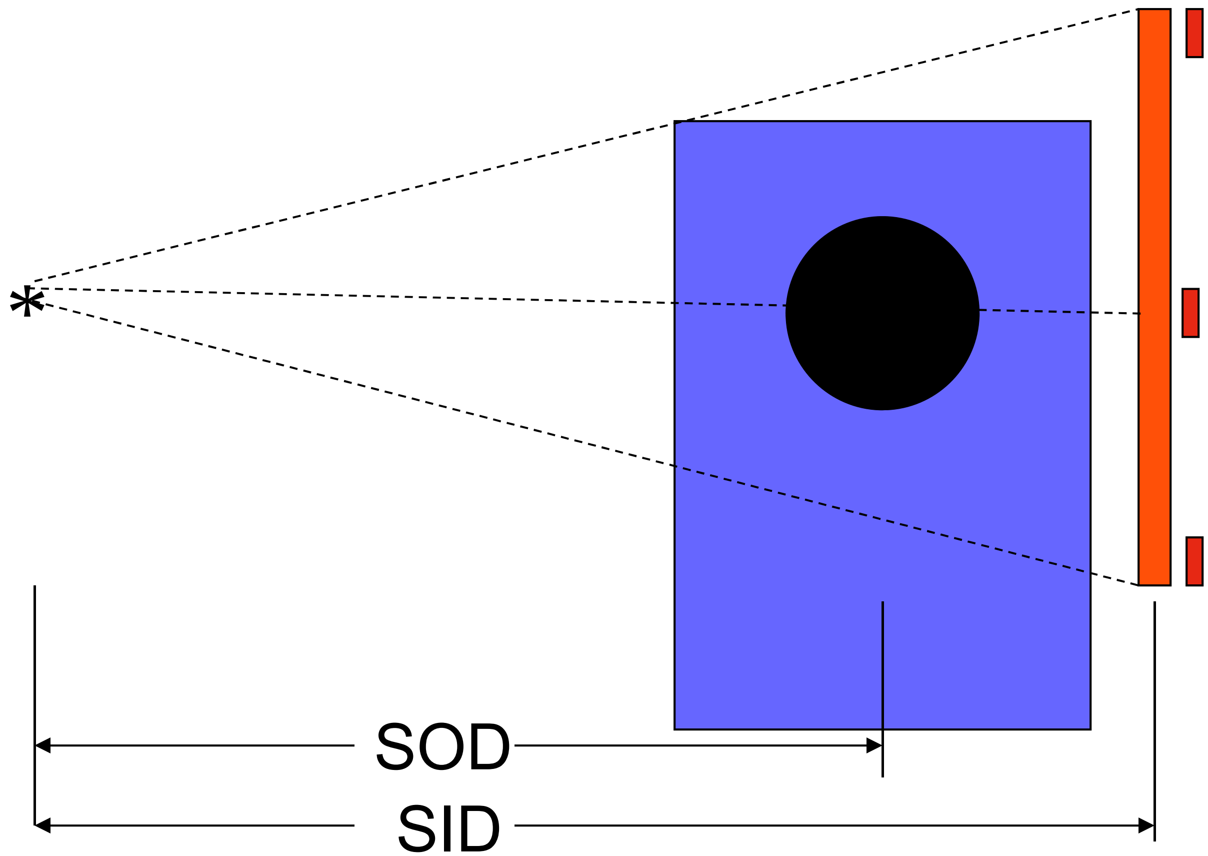
X-ray Filtering



Scatter Reduction Strategies



Dose Estimation



Dose Estimation (cont'd)

Machine Output: $\boxed{}$ @ 1 meter

Source to Image Distance (SID): $\boxed{}$ meters

Unattenuated Beam at Image

= (Machine Output @ 1 m)/(SID in meters)^2

$$= \boxed{} / \boxed{}^2 = \boxed{}$$

Dose Estimation (cont'd)

HVLs of material 1:

HVLs of material 2:

HVLs of material 3:

Total Attenuation = $(\frac{1}{2}^{HVL1})(\frac{1}{2}^{HVL2})(\frac{1}{2}^{HVL3})$

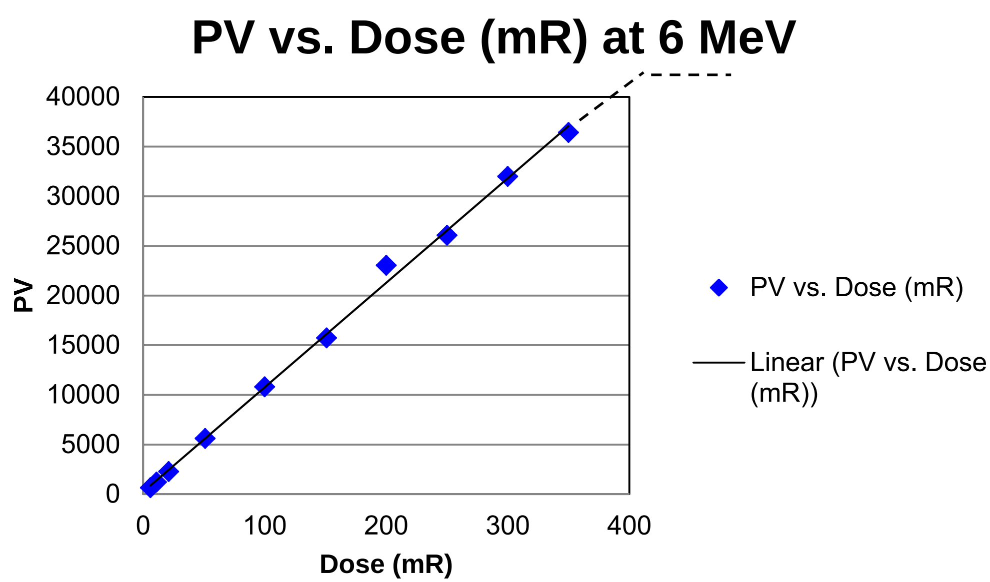
Dose Rate at Image:

= Unattenuated Beam * Total Attenuation

= * ½ * ½ * ½ =

Scan-X Rudiments

- **Produces positive linear radiographs**
  - Pixel value increases with dose
  - Pixel brightness increases with dose
    - Larger PV means greater brightness
  - PV is linear with dose



Scan-X Rudiments (cont'd)

- **Produces positive linear radiographs**
  - Pixel Value increases with dose
  - Pixel brightness increases with dose
    - Larger PV means greater brightness
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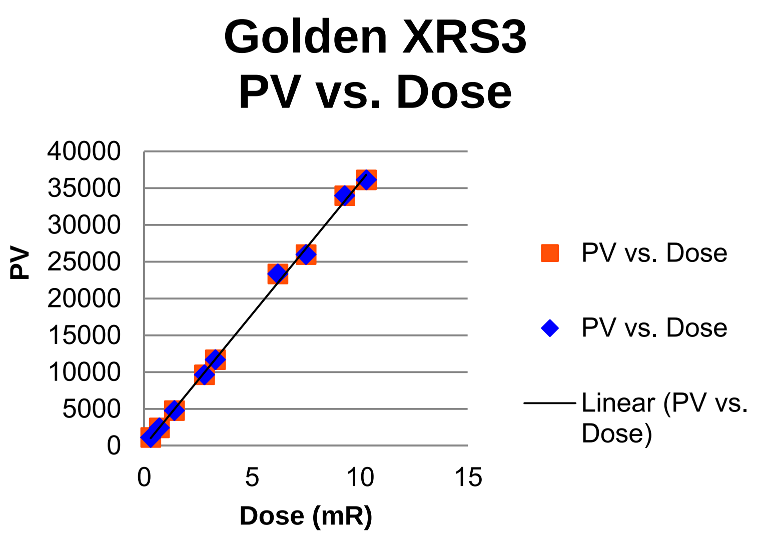
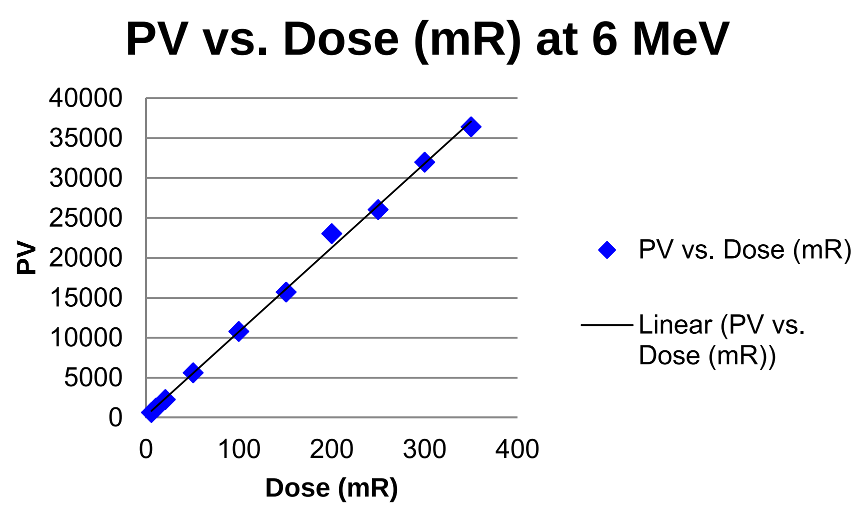
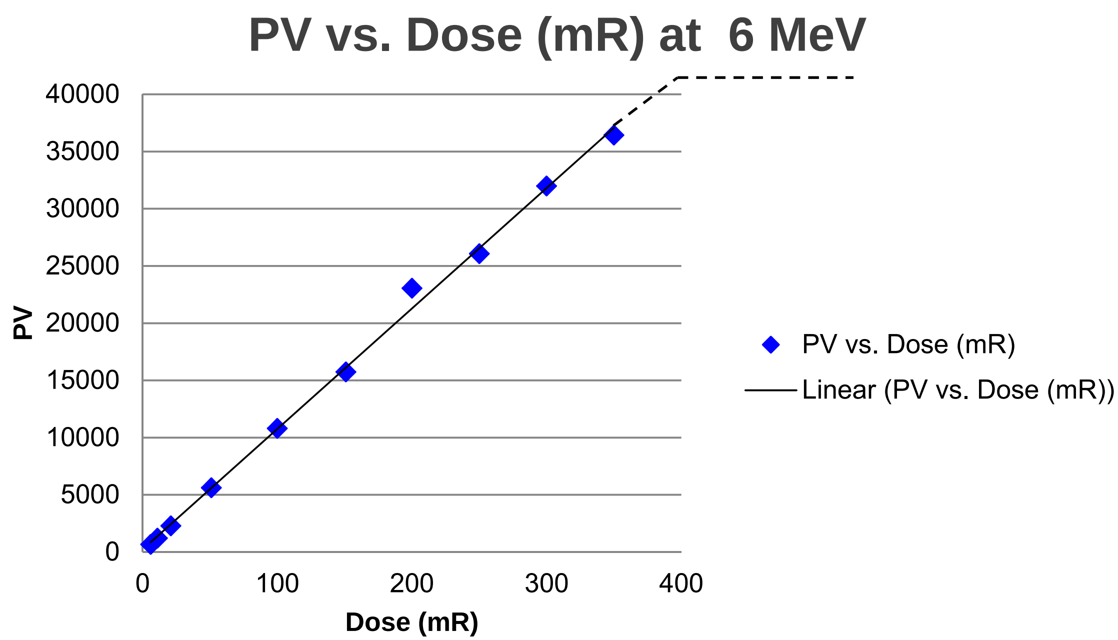




Dose Estimation



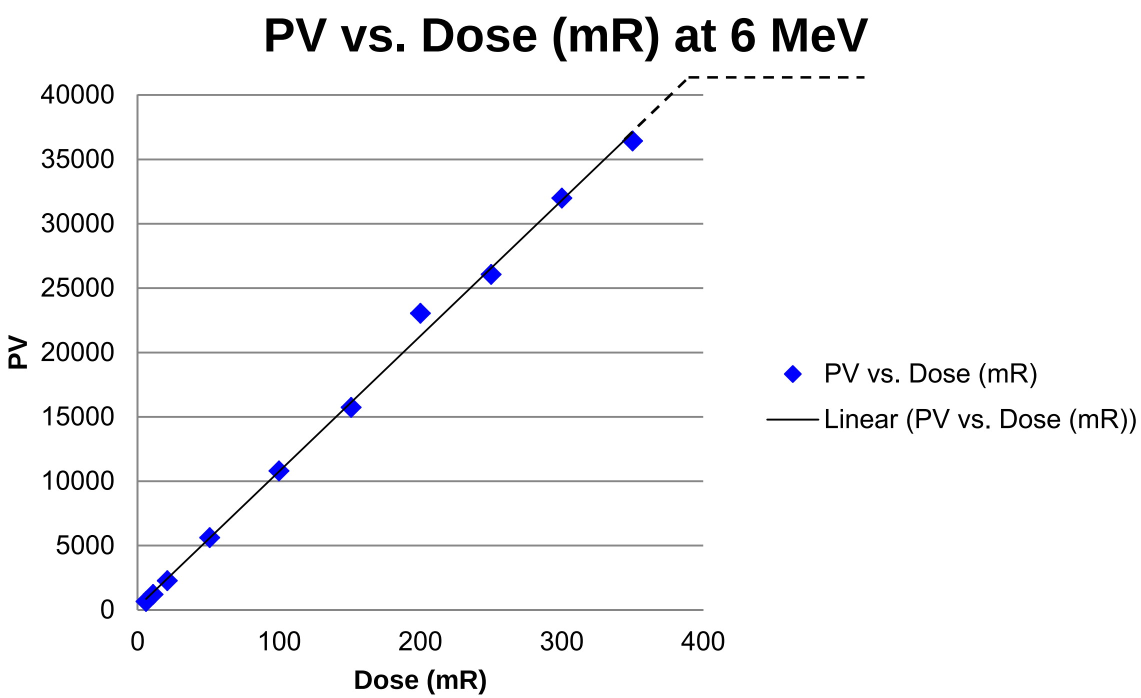
Approximate Time of Exposure:

(Dose Desired)
(Dose Rate at Image)

Put Radcal behind area of interest – stop exposure if time significantly exceeded

- 400 mR = 4 mGy gives signal of about 40000
- Saturation at about 400 mR = 4.5 mGy gives signal of 40940
- Remember that noise decreases as dose to phosphor increases

Dose Estimation (cont'd)



Approximate Time of Exposure:

(Dose Desired)
(Dose Rate at Image)

Put Radcal behind area of interest – stop exposure if time significantly exceeded

Remember that noise decreases as dose to phosphor increases

Inverse Square Factors

Feet to Meters: Multiply feet by 0.305 (or divide feet by 3.28)

Inches to Meters: Multiply inches by 0.0254 (or divide inches by 39.4)

Common Distances:

1.8 meters	$(1/r^2 \sim 1/3)$
3.1 meters	$(1/r^2 \sim 1/10)$
3.7 meters	$(1/r^2 \sim 1/13)$
4.6 meters	$(1/r^2 \sim 1/20)$
6.1 meters	$(1/r^2 \sim 1/40)$
9.2 meters	$(1/r^2 \sim 1/85)$

Inverse Square Factors (cont'd)

Feet to Meters: Multiply feet by 0.305 (or divide feet by 3.28)

Inches to Meters: Multiply Hidden slide .0254 (or divide inches by 39.4)

Common Distances:

6 feet = 72 inches = **1.83 meters** ($1/r^2 \sim 1/3$)

10 feet = 120 inches = **3.05 meters** ($1/r^2 \sim 1/10$)

12 feet = 144 inches = **3.66 meters** ($1/r^2 \sim 1/13$)

15 feet = 180 inches = **4.57 meters** ($1/r^2 \sim 1/20$)

20 feet = 240 inches = **6.10 meters** ($1/r^2 \sim 1/40$)

30 feet = 360 inches = **9.15 meters** ($1/r^2 \sim 1/85$)

Lesson Summary

- **Contrast is the information in the image**
- **X-ray energy affects contrast**
- **Scatter affects contrast negatively**
  - Obscures the image
  - Try to reduce scatter
- **Size of feature and its contrast define the ability to detect the feature**

X-ray Energy Experiments

- Carbon, aluminum, steel, tungsten, lead
- Equal thicknesses at different energies
- Step wedges at different energies
- Filters

STABILIZATION PROGRAM
NNSA NA-42

Betatron Course

Lesson 5

Signal and Noise

Lesson Objectives

1. Identify the effect “noise” has on a radiograph
2. Identify the factors that contribute to noise
3. Identify techniques that can reduce noise in a radiograph

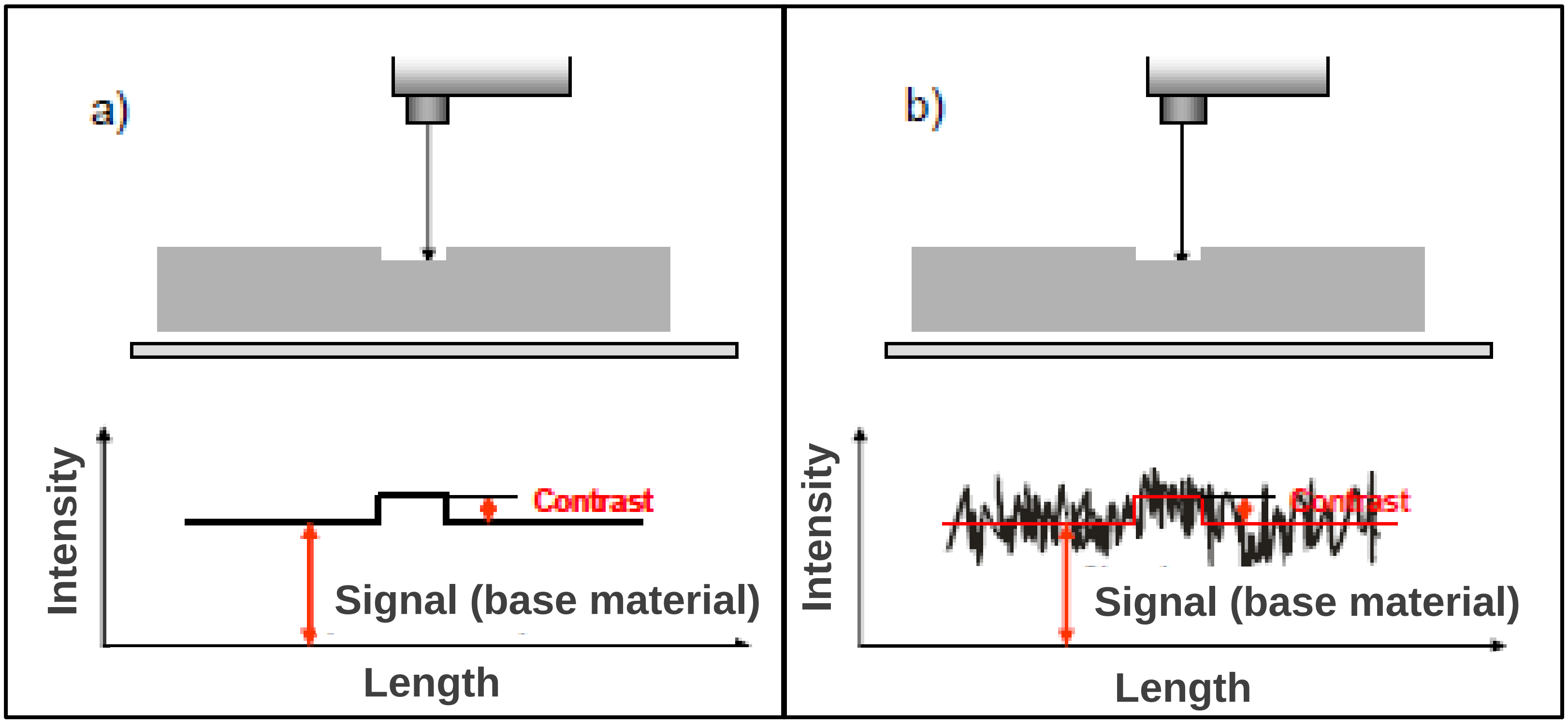
Main Ideas

- **Noise is one of the major factors determining the ability to detect details in radiographs**
- **Noise is dependent on x-ray dose delivered to the image**
- **More dose = better image (up to a point)**
  - BUT phosphor systems saturate so dose must be below the saturation dose

Signals within Noise

- **Radiowave detection**
  - Signal = music
  - Noise = static
- **Same principal but radio is signal in time**
- **Image is signal in space**

Noise in Radiographs



Notch visible!

Contrast/Noise is high
Signal/Noise is high

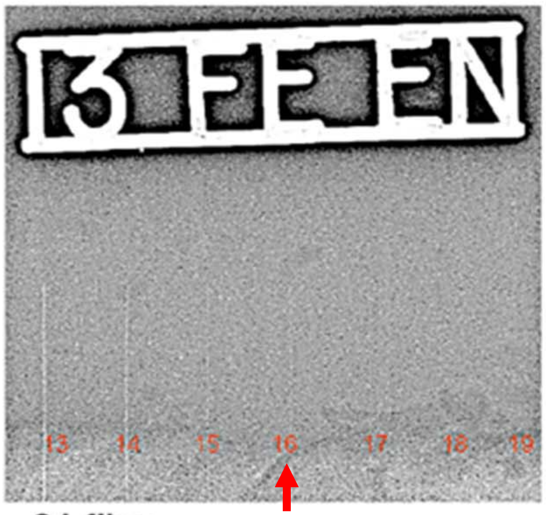
Notch not visible!

Contrast/Noise is low
Signal/Noise is low

Detecting Features

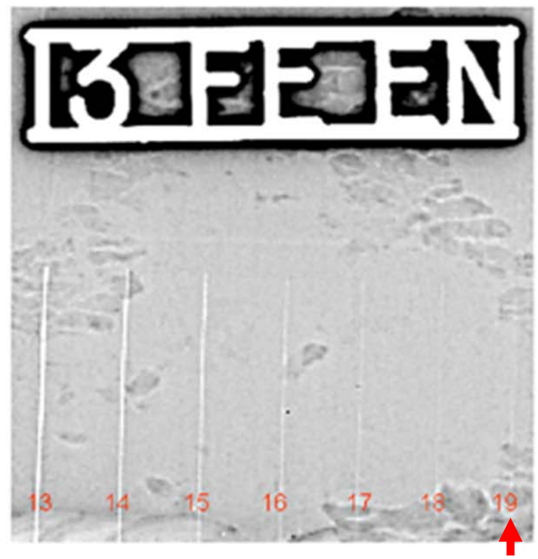
Smaller than One Pixel

Lower noise enables lower contrast features to be detected even with larger pixels!



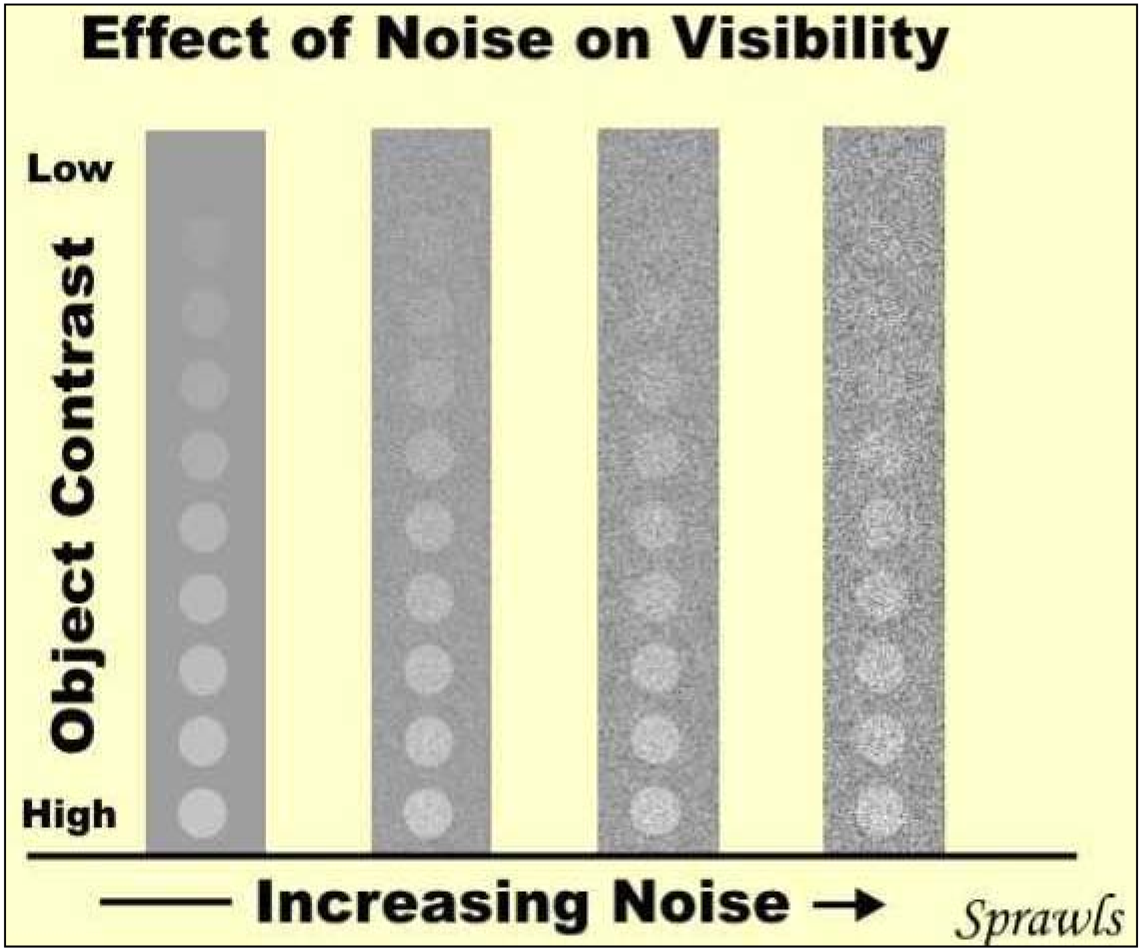
C1 film
Wire 16 visible
100µm contrast res.

highpass filtered



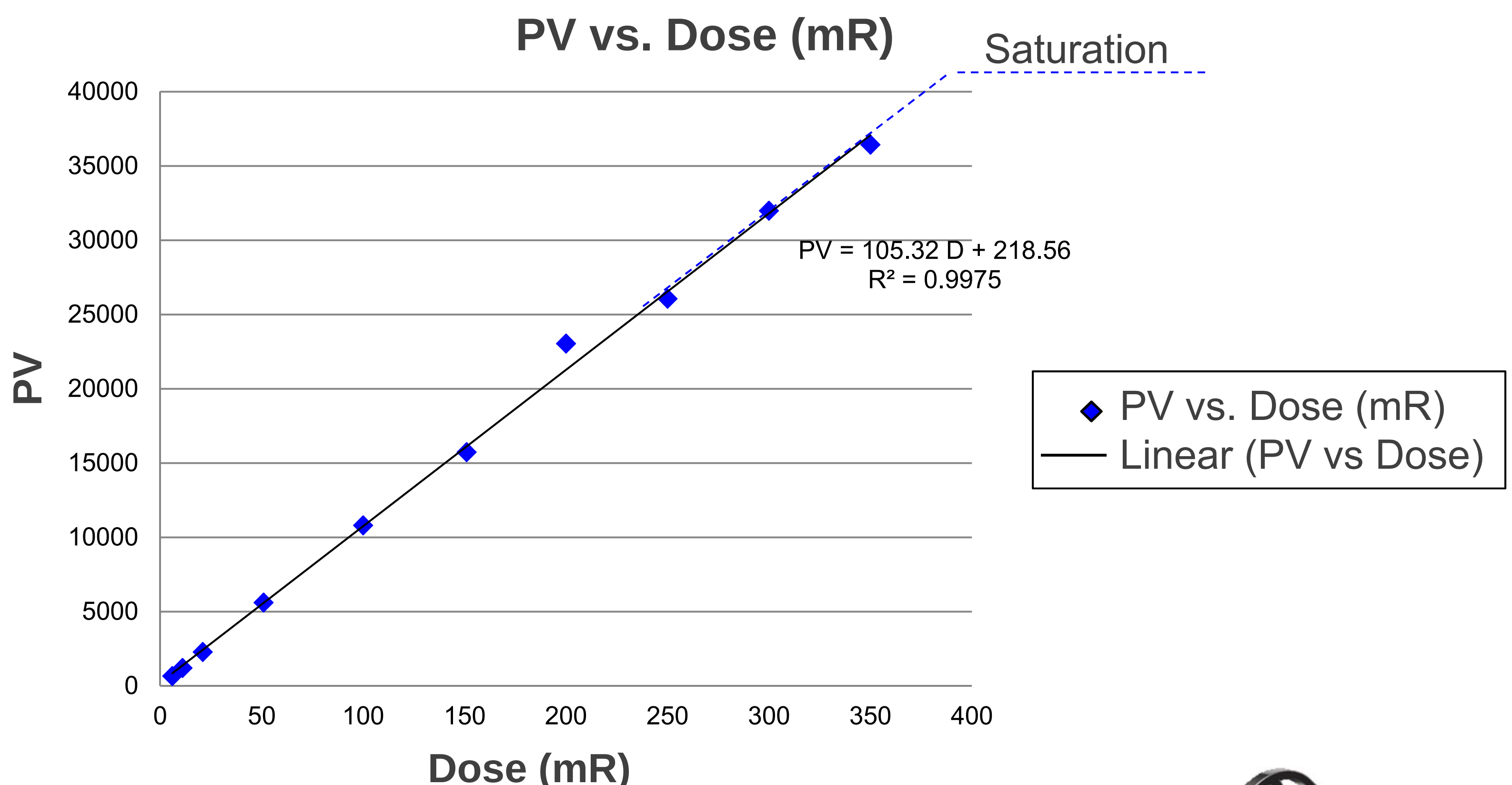
DDA (magnification = 1)
Wire 19 = 50µm contrast res.
200µm pixel size!

Image Noise

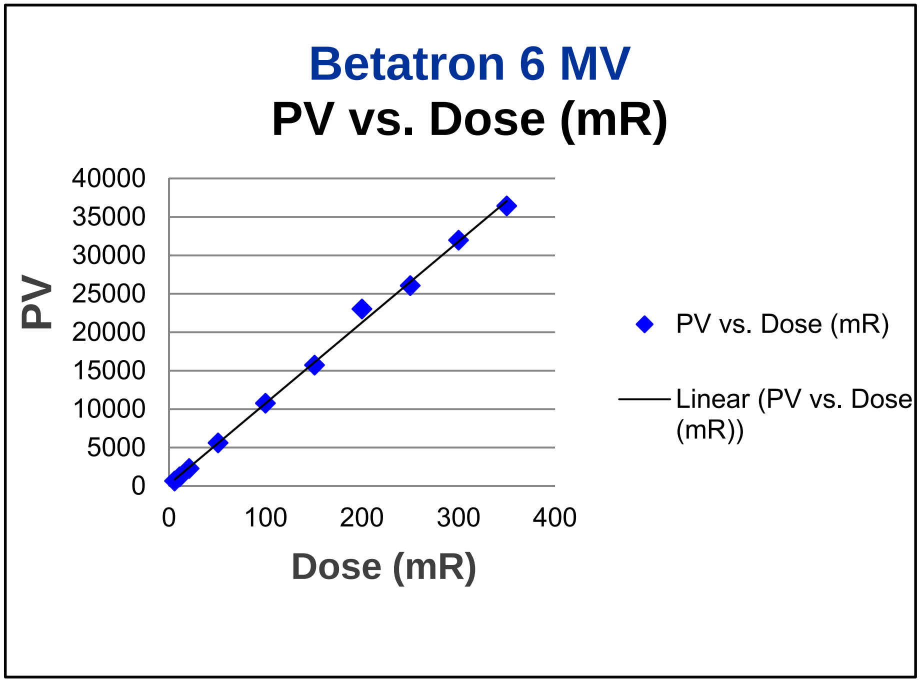


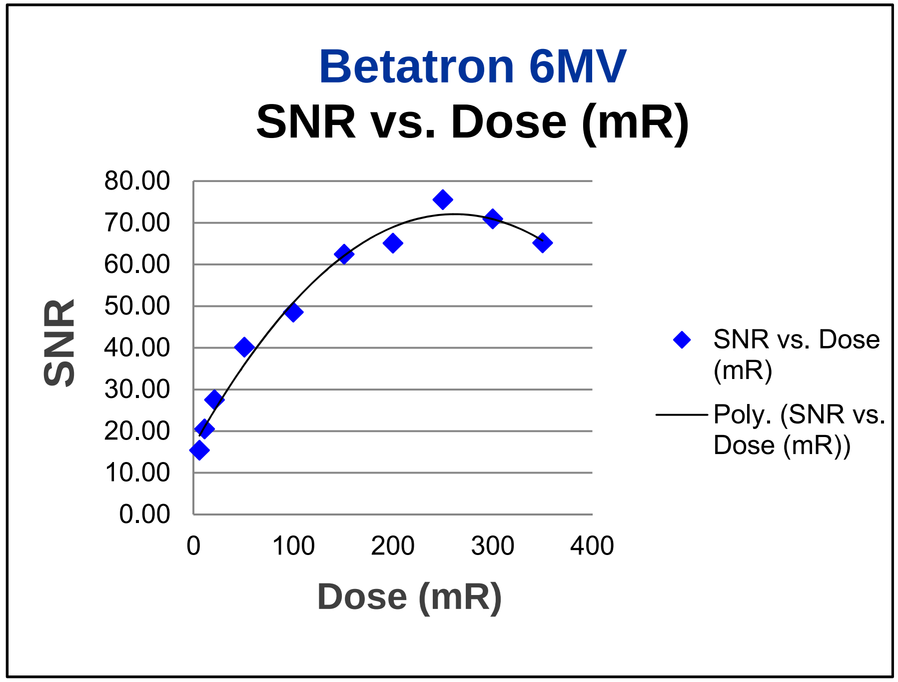
Effect of Noise on Visibility
Low
Object Contrast
High
Increasing Noise →
Sprawls

ScanX Scanner: Linear with Dose



ScanX with XTK Standard Mode





ScanX Scout Scanner

PV Linear with Dose – SNR √Dose

3.3 mSv (330 mR) incident on 51mm (2 in.) steel with 6 MeV

~1 mSv (100 mR) on IP (HVL = 29.2mm (1.15 in.)

PV ~10000 SNR ~40

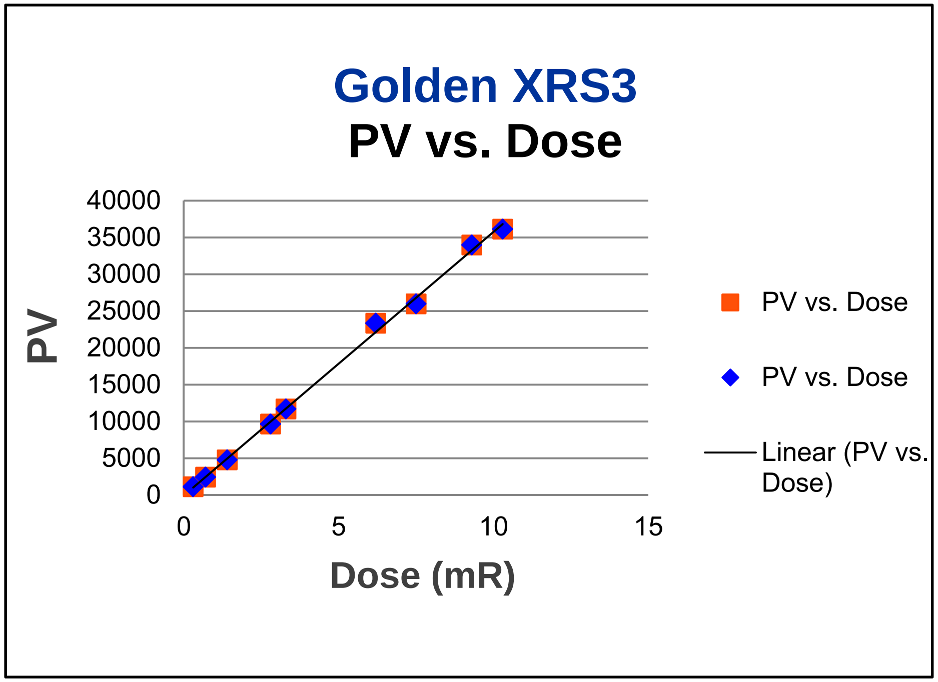
10 mSv (1000 mR) – 3X dose – Incident on 51mm (2 in.) steel with 6 MeV

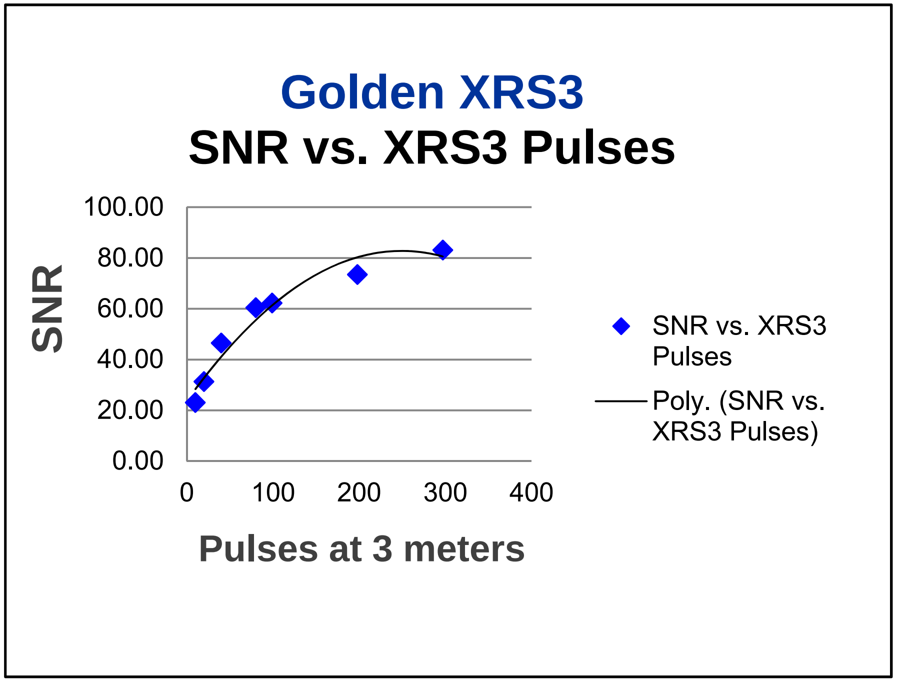
~3 mSv (300 mR) on IP

PV ~30000 (3X) SNR ~70 (1.75X) [√3 = 1.73]

STABILIZATION PROGRAM NNSA NA-42

ScanX with XTK Standard Mode





Standard Test Plate

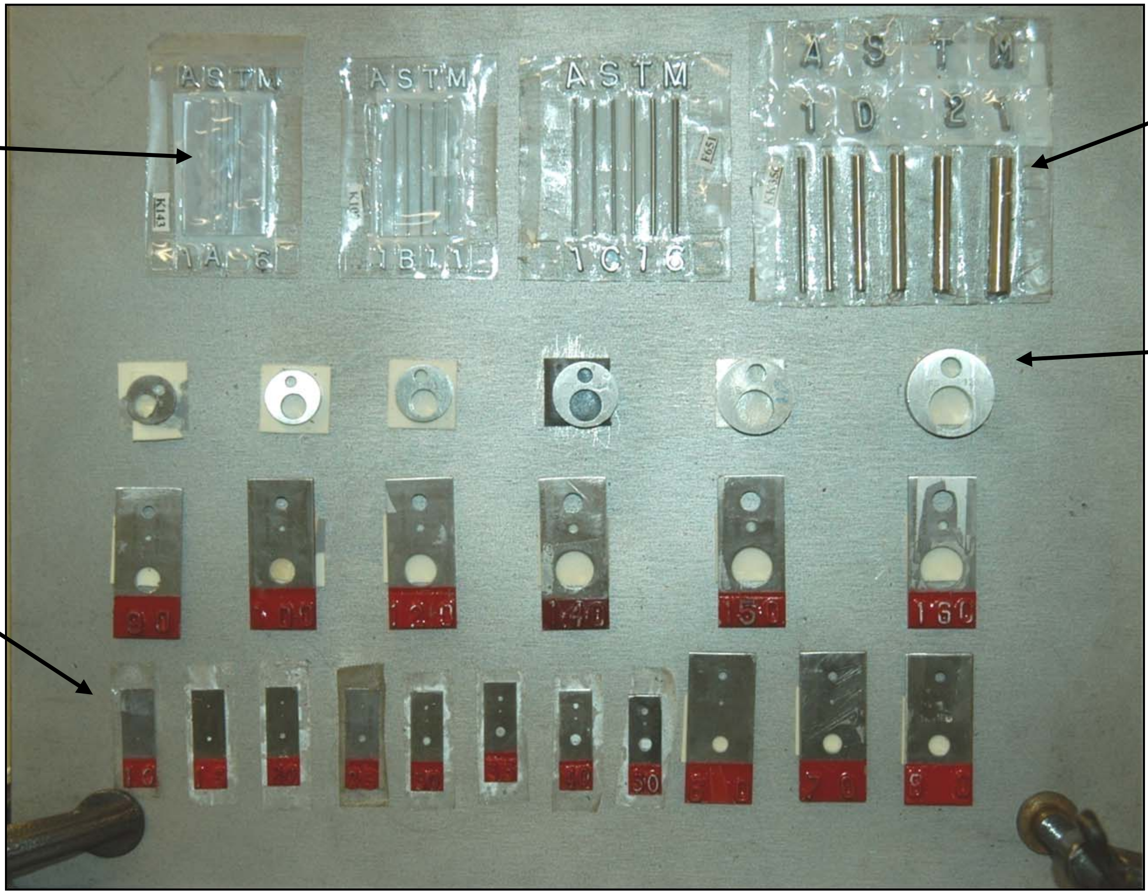
36cm x 43cm steel plate with hole and wire penetrameters

0.08mm

8.1mm

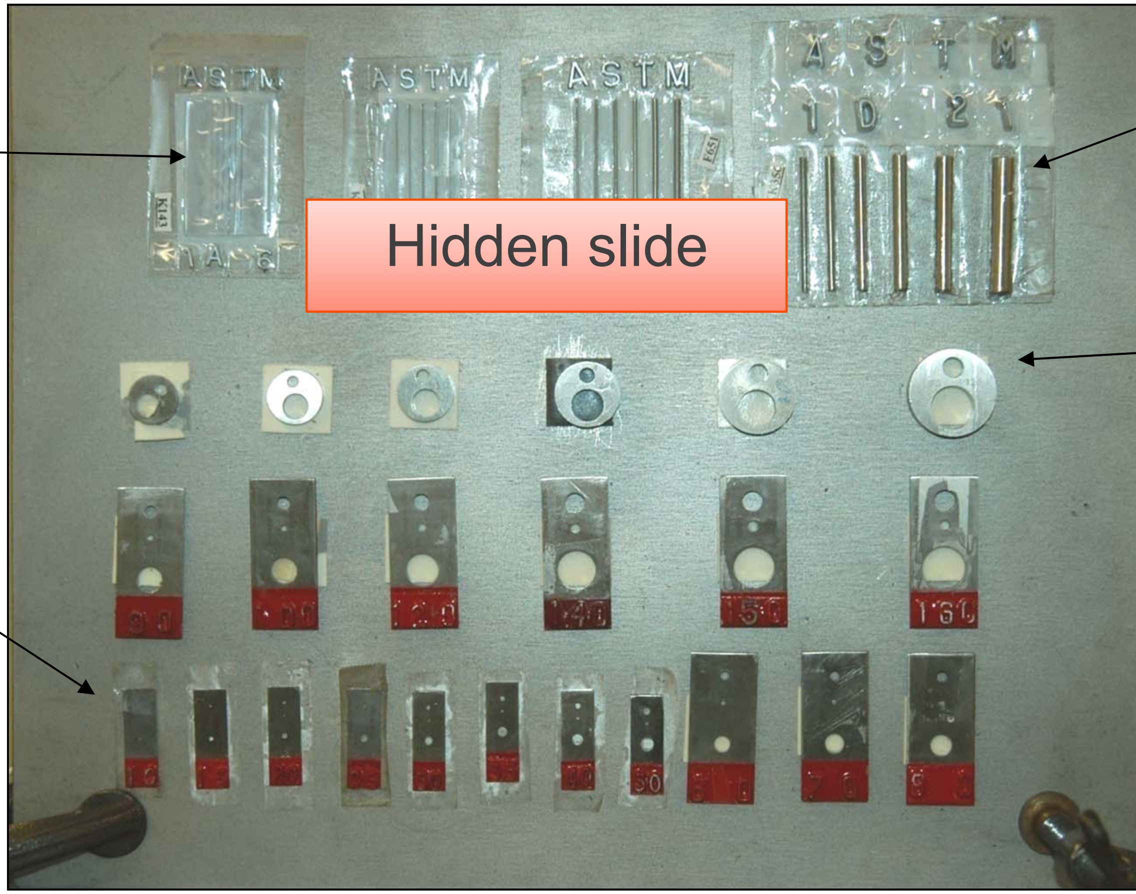
8.1mm

0.23mm



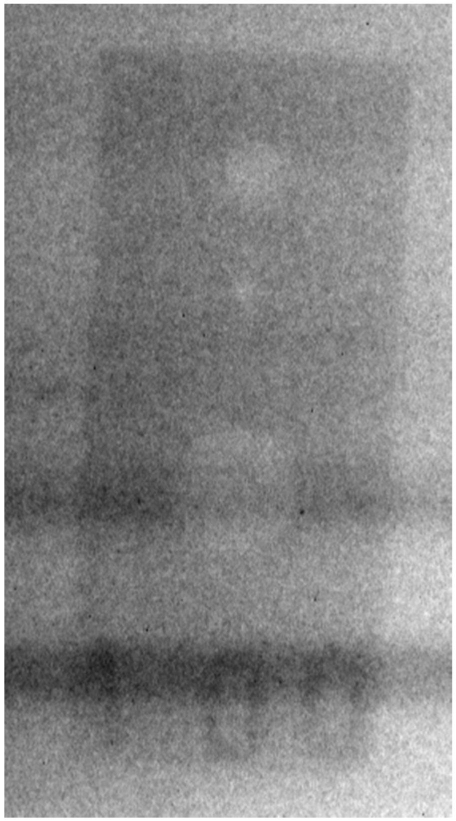
Standard Test Plate

14" x 1" steel plate with hole and wire penetrameters

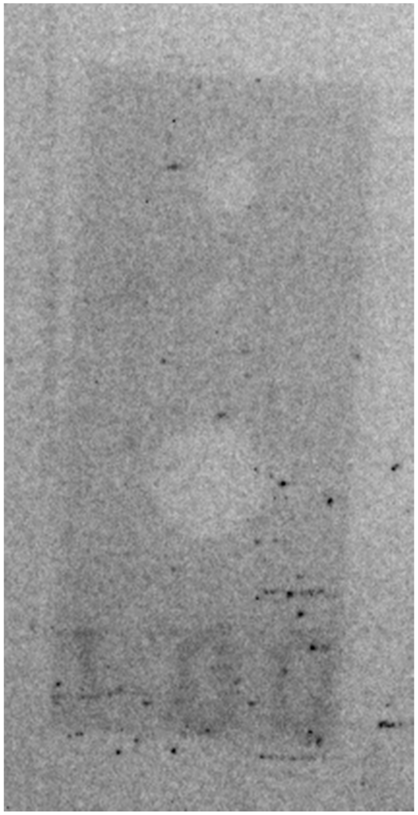


Comparison

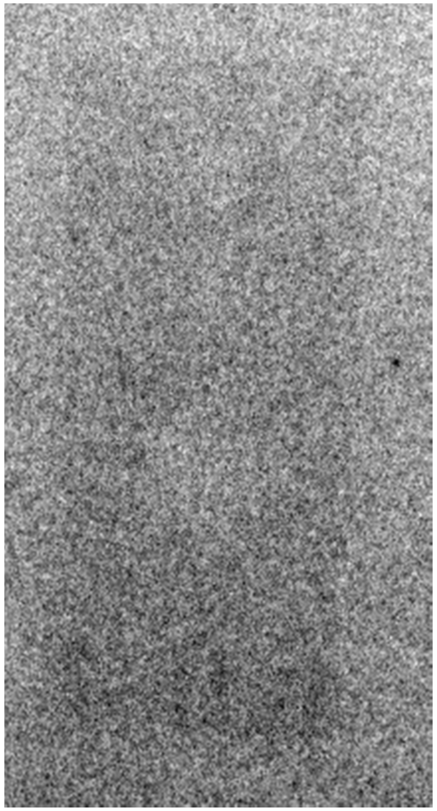
Scan X Std Res
10 mSv (SNR~90)



ACR2000
10 mSv (SNR~70)

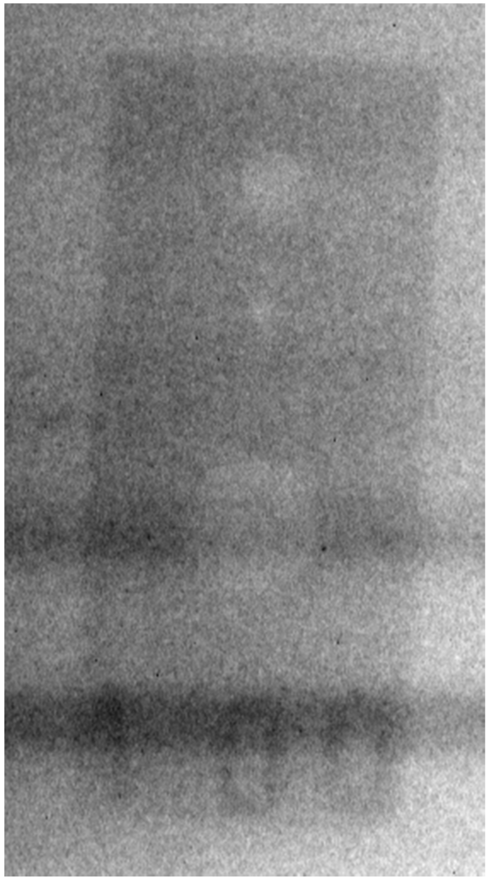


ACR2000
0.63 mSv (SNR~25)

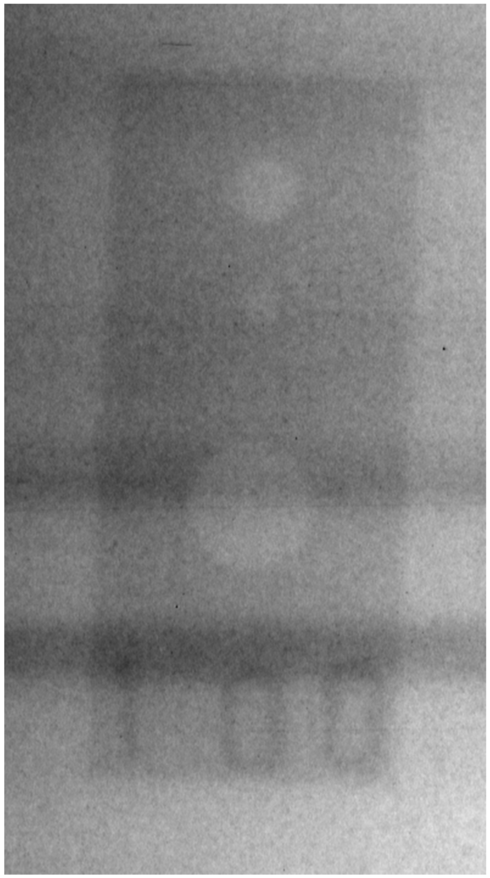


Comparison (cont'd)

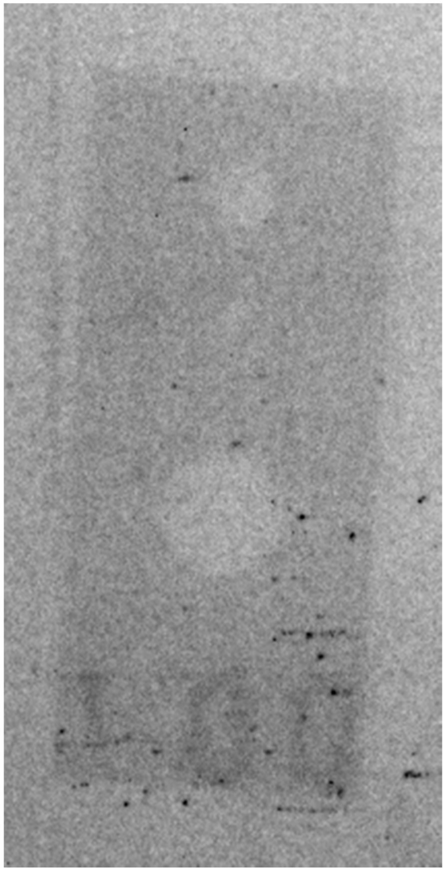
Scan X Std Res
10 mSv (SNR~90)



ScanX 50 Micron Res
20 mSv (SNR~110)



ACR2000
10 mSv (SNR~70)



Application

- Thicker/denser features will have more noise
- May need to saturate thinner/less dense features in order to get low noise in thicker/denser features

Summary

- **Noise is dependent on x-ray dose delivered to the image**
- **More dose = better image (up to a point)**
  - BUT phosphor systems saturate so dose must be below the saturation dose

Practical

- SNR and EPS vs. Dose/PV
- Penetrameter Plates

Betatron Course

Lesson 6

Radiographic Setup

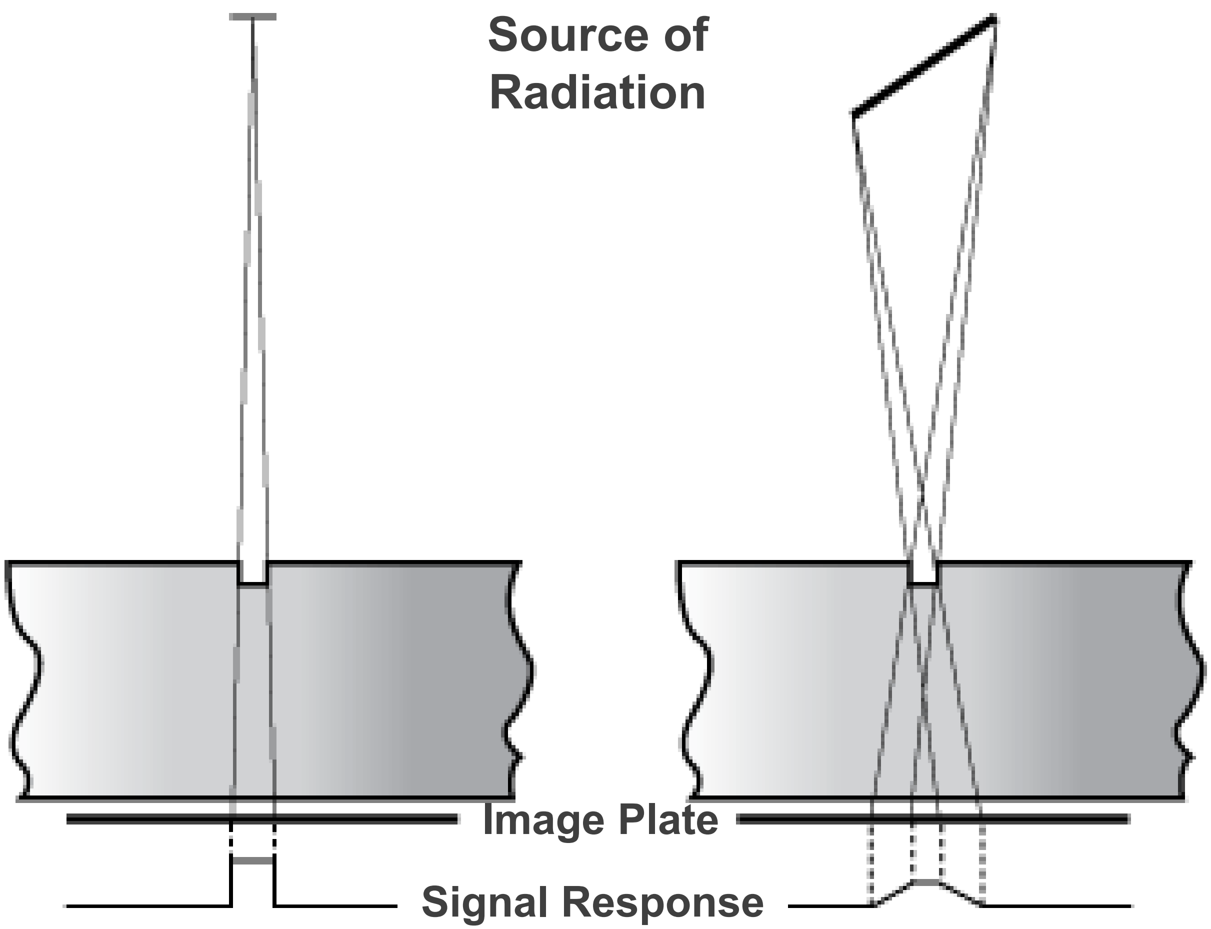
Lesson Objectives

1. Identify factors that affect **blurring** of a radiographic image
2. Identify the effects **distances in an x-ray set-up** can have on a radiographic image
3. Identify the effects **angle and rotation** have on a radiographic image

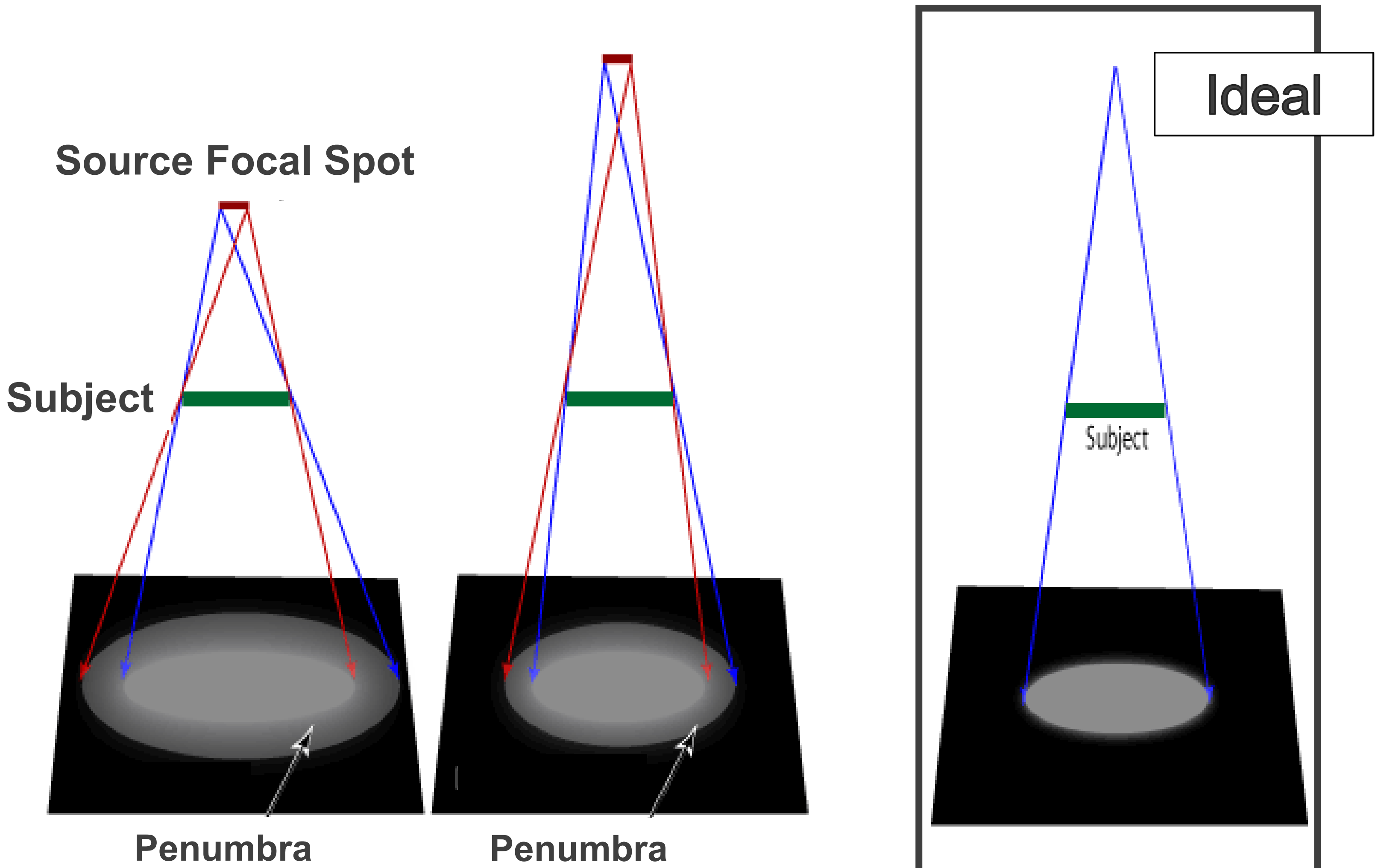
Main Ideas

- **Focal Spot Size**
  - Affects blur
- **Distance Focal Spot to Imager**
  - Affects blur
  - Affects exposure ($1/r^2$)
  - Affects field of view
- **Distance Object to Image**
  - Affects blur
  - Affects scatter
- **View Angle and Rotation**
  - Affects distortion/parallax
  - Affects overlap

Unsharpness/Blur



Unsharpness/Blur (cont'd)



Pixels

Three types of pixels

1. **Detector Pixel**

   Where the signal originates: larger area than the pixel location

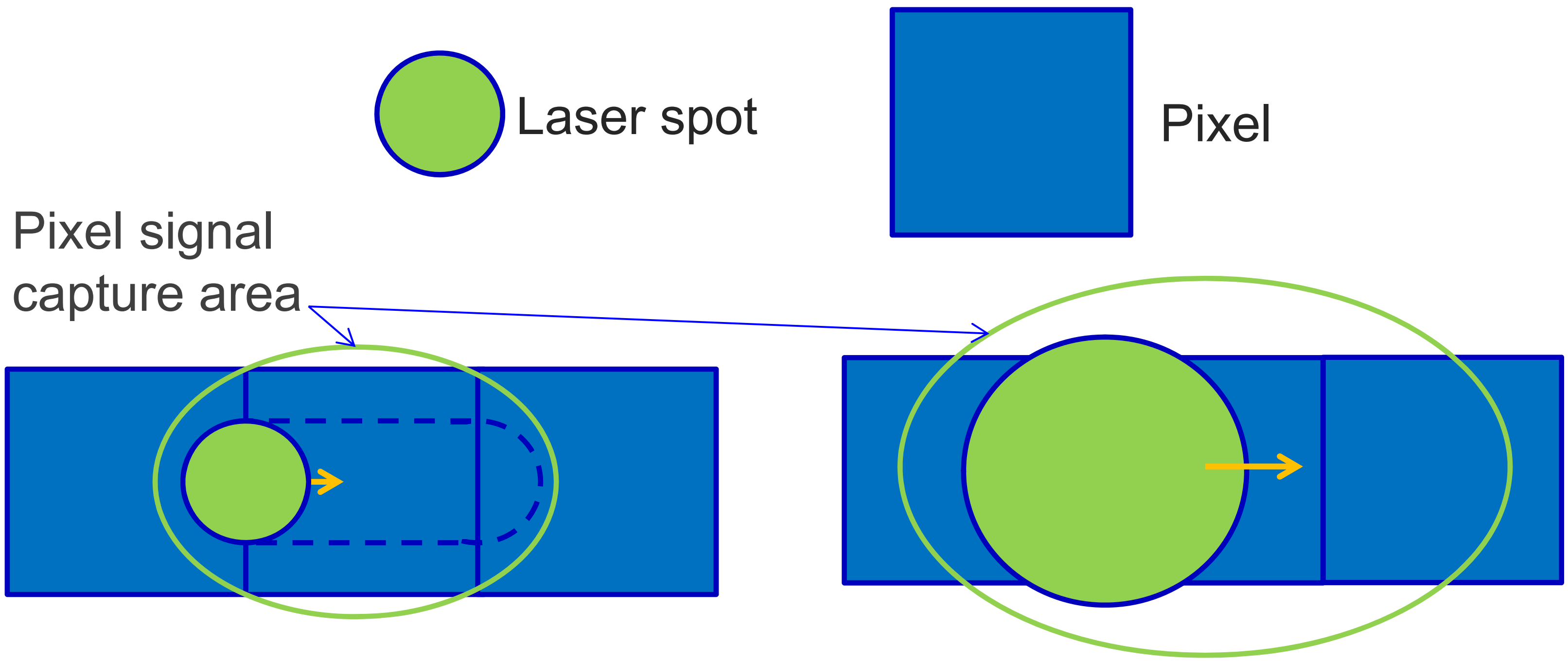
2. **Image Pixel**

3. **Display Pixel**

Pixels (cont'd)

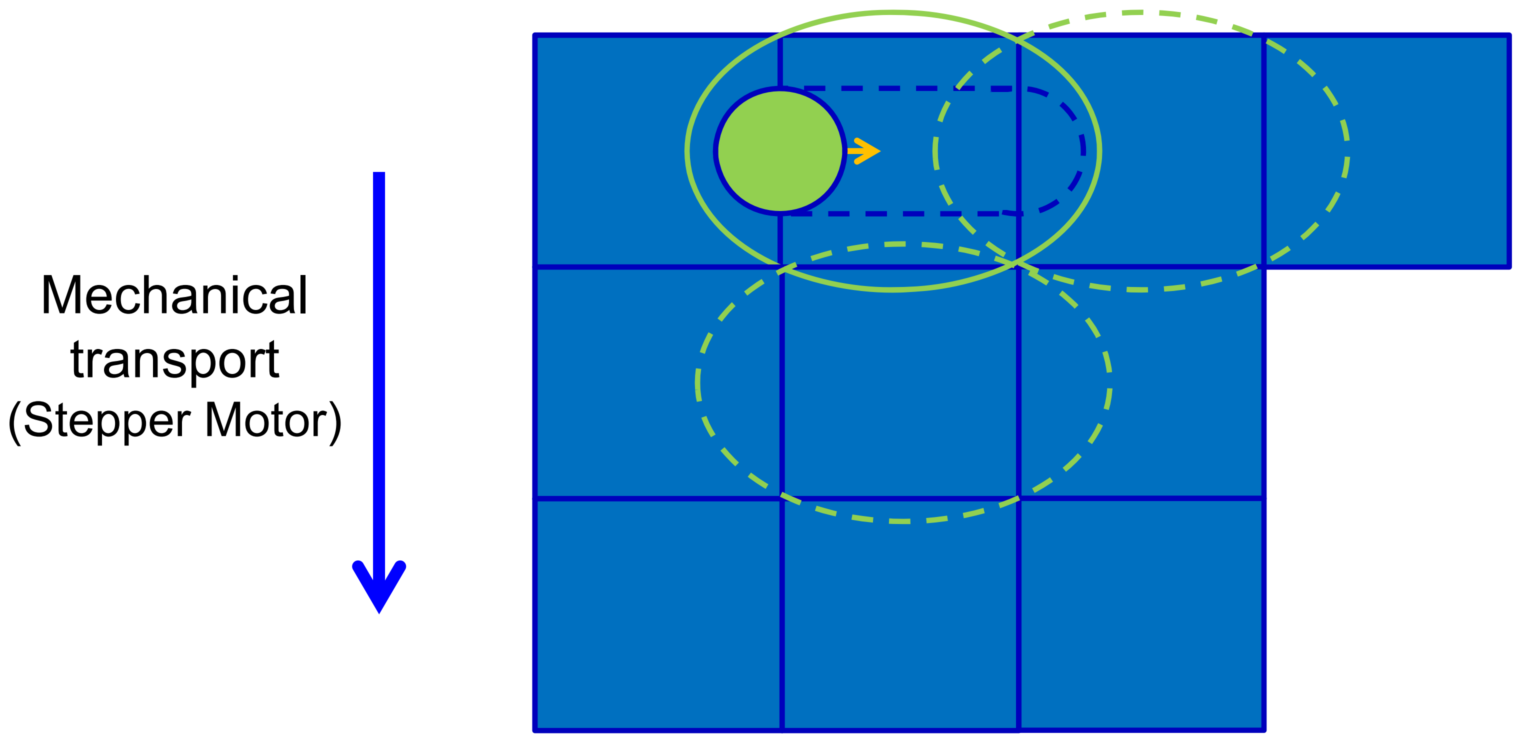
Computed Radiography Detector Pixel

Where the signal originates: larger area than the pixel location



Pixels and SR_B

Computed Radiography Detector Pixel



Pixels (cont'd)

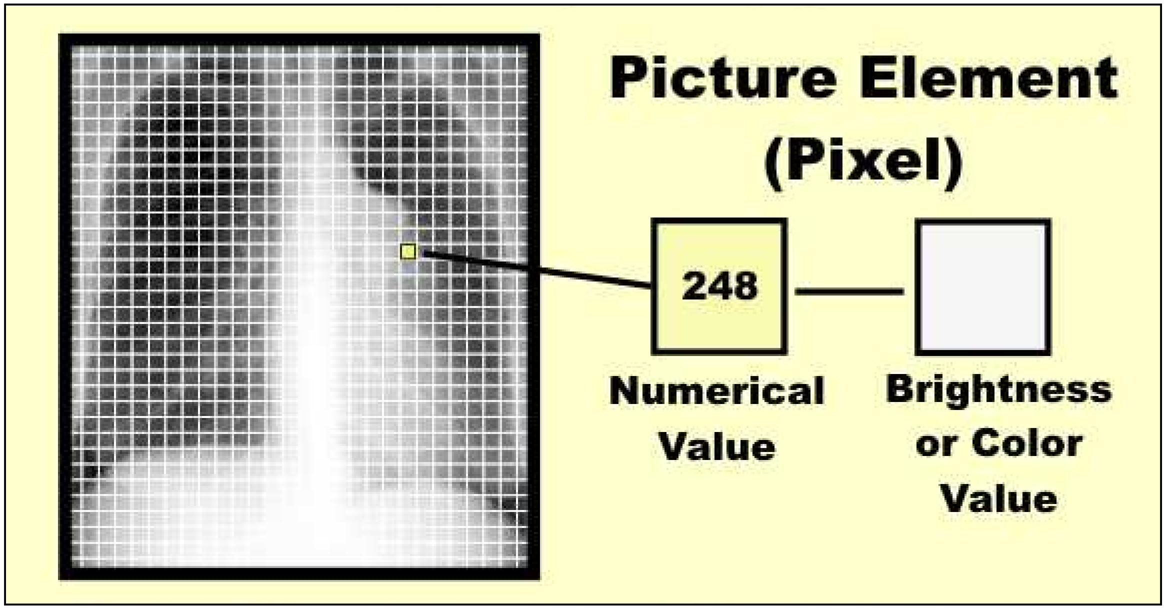
Detector Pixel

- Where the signal originates: larger area than the pixel location

Image Pixel

- Numbers in a matrix: Pixel Value (PV) and Location

Display Pixel



Pixels (cont'd)

Detector Pixel

- Where the signal originates: larger area than the pixel location

Image Pixel

- Numbers in a matrix: Pixel Value (PV) and Location

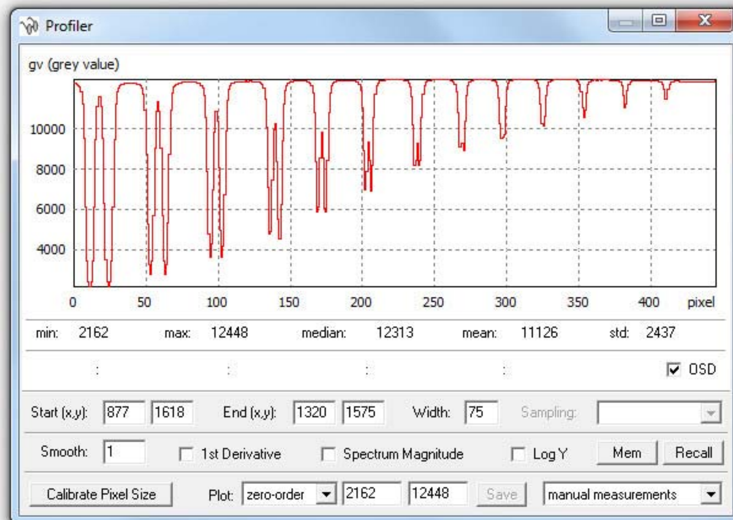
Display Pixel

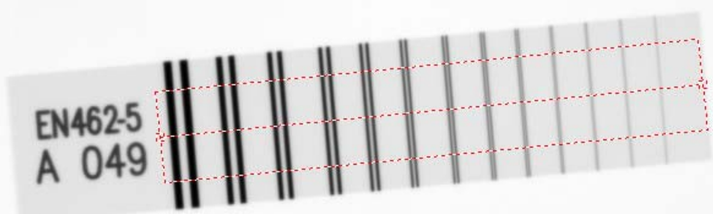
- Pixel value translated into a brightness at a location

Standard Measurement of Resolution of Scanner

ASTM E2002 or ISO 19232-5

Duplex Wire Gauge

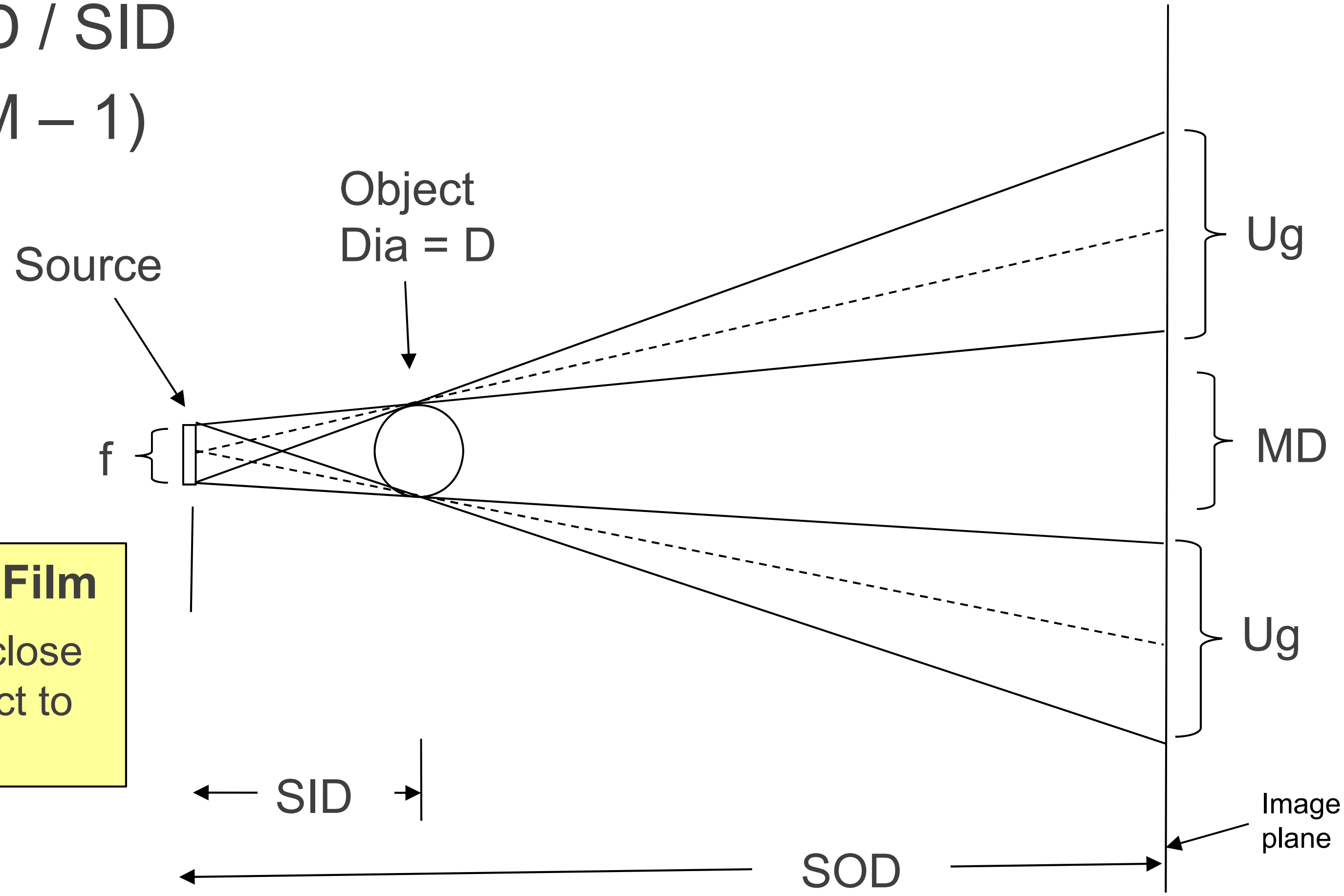




Duplex Wire Gauge

Imaging Geometry

- M = SOD / SID
- Ug = f (M – 1)

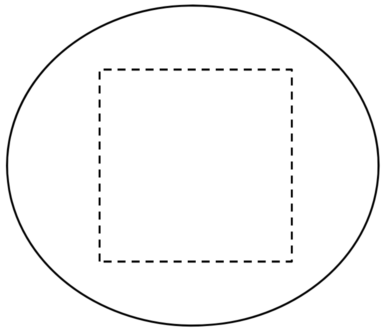


General Rule for Film

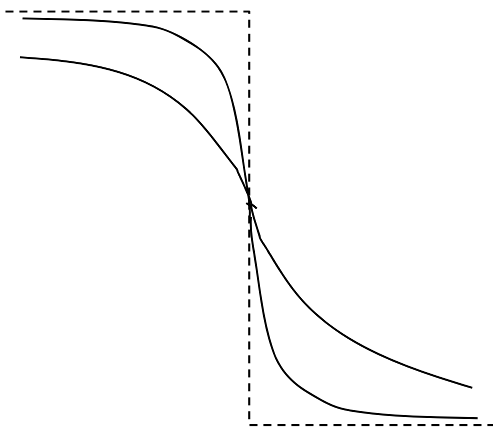
Image detector as close as possible to object to minimize Ug

Total Unsharpness

- $Ut = \sqrt{Ug^2 + (2\ SRb)^2}$
  - SRb = basic Spatial Resolution of image detector
  - SRb > pixel dimension

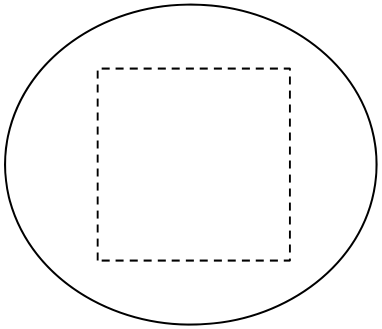


- **Edge blur**
- **Due to**
  - Secondary radiation
  - Internal scatter
  - Light spreading
  - Detector pixel overlap (scanning)



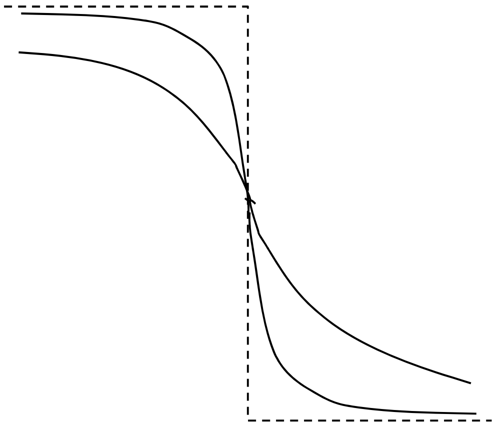
Total Unsharpness (cont'd)

- $Ut = \sqrt{Ug^2 + (2\ SRb)^2}$

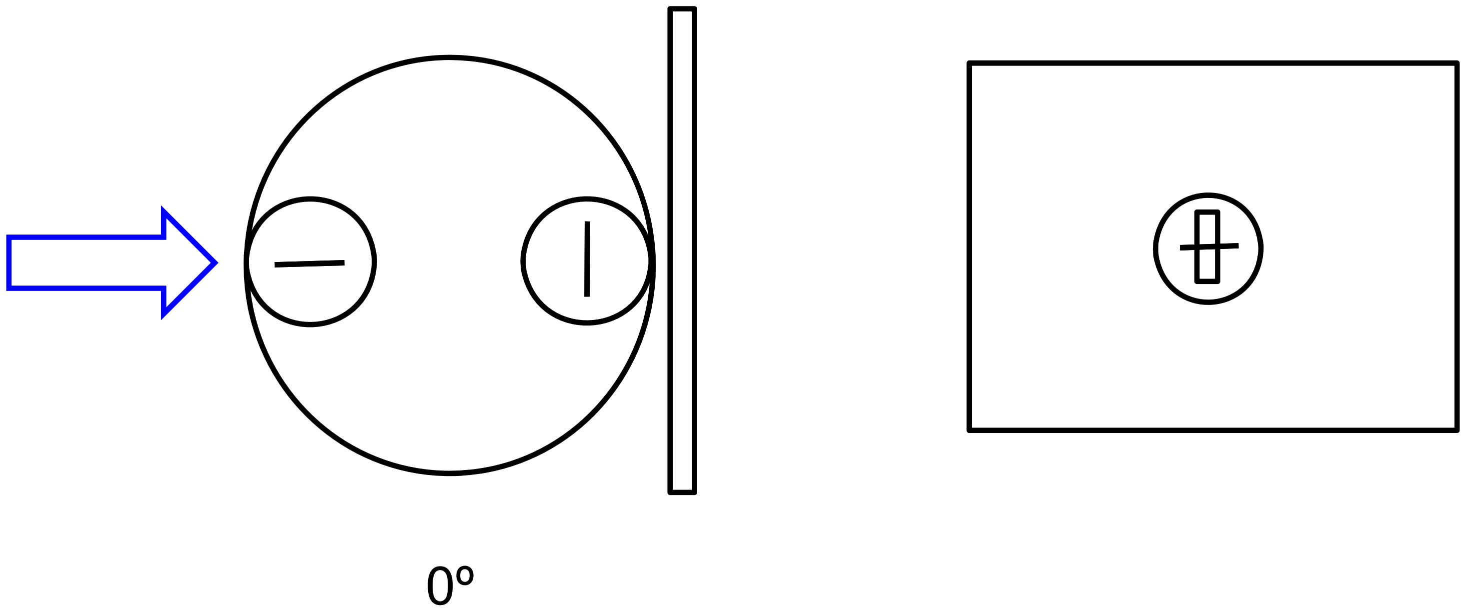


- **Example:**
  - ScanX using XTK and GP Image Plate
  - Pixel dimension = 175 µm
  - SRb = 200 µm

  - SRb of x-ray film is ~ 5 -10 µm
  - SRb also dependent on x-ray energy

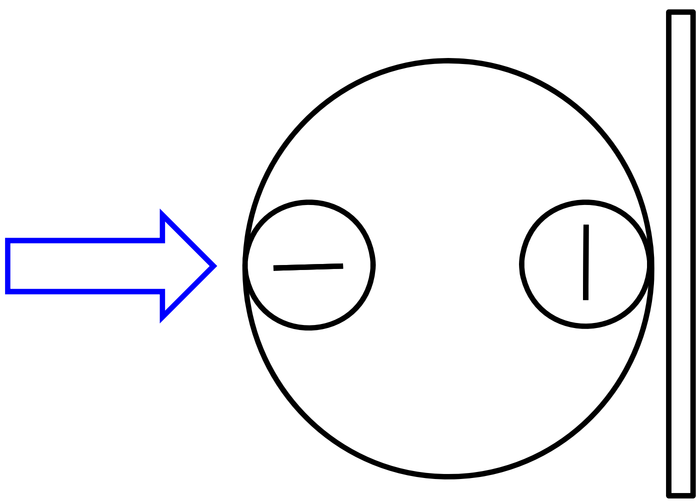


Views

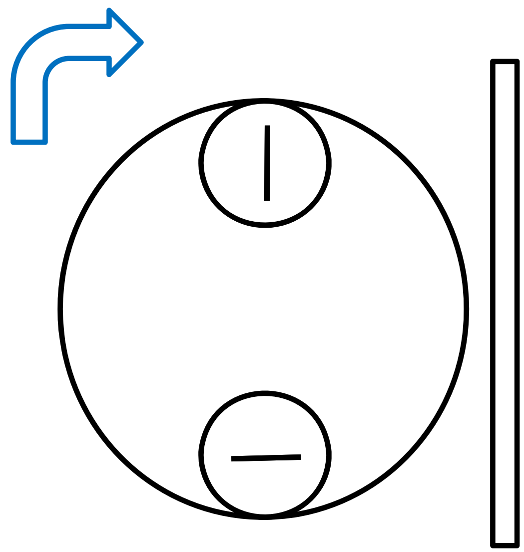


Views (cont'd)

Knowing location of components and best angle of beam is as or more important as the radiographic technique

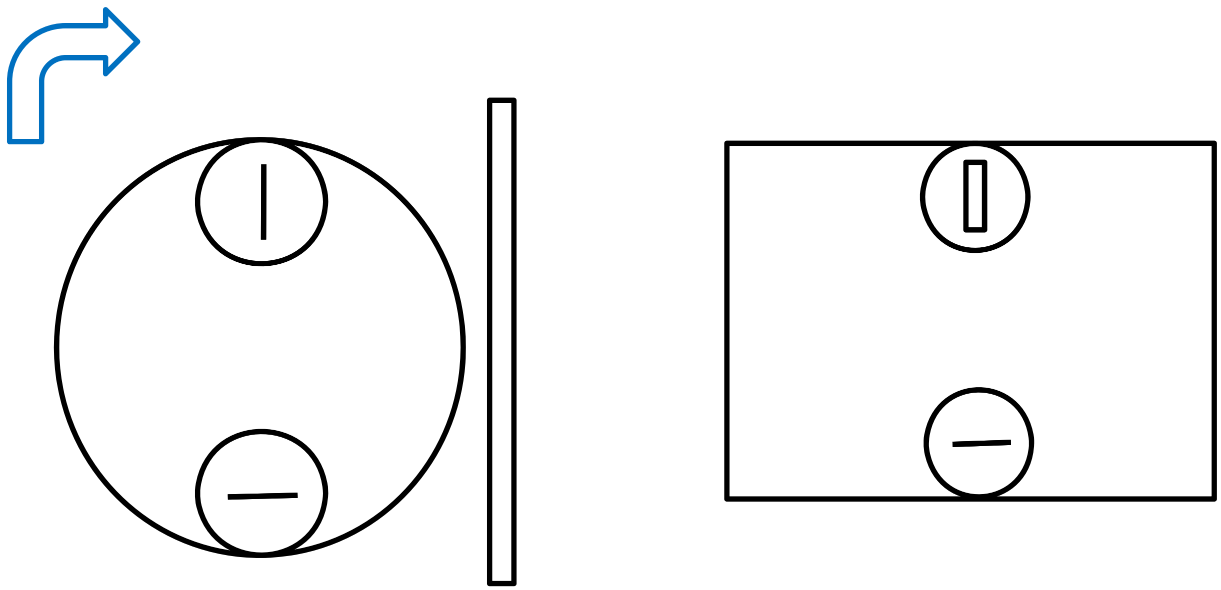


0º



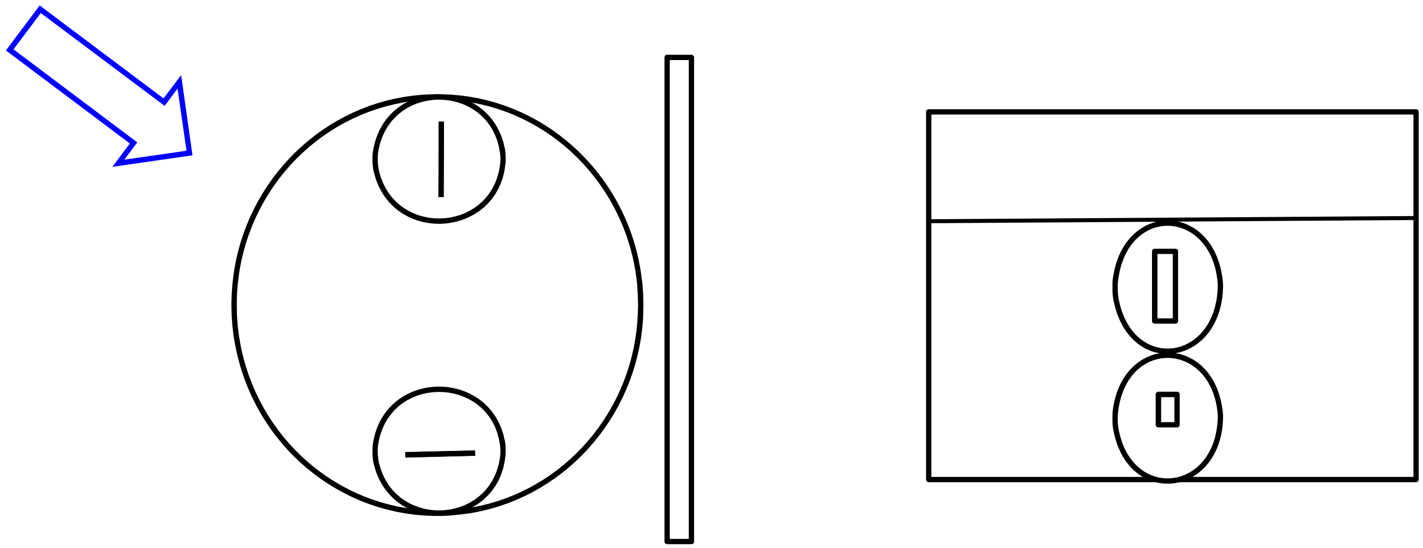
Rotated 90º CW

Views (cont'd)



Rotated 90º CW

Views (cont'd)

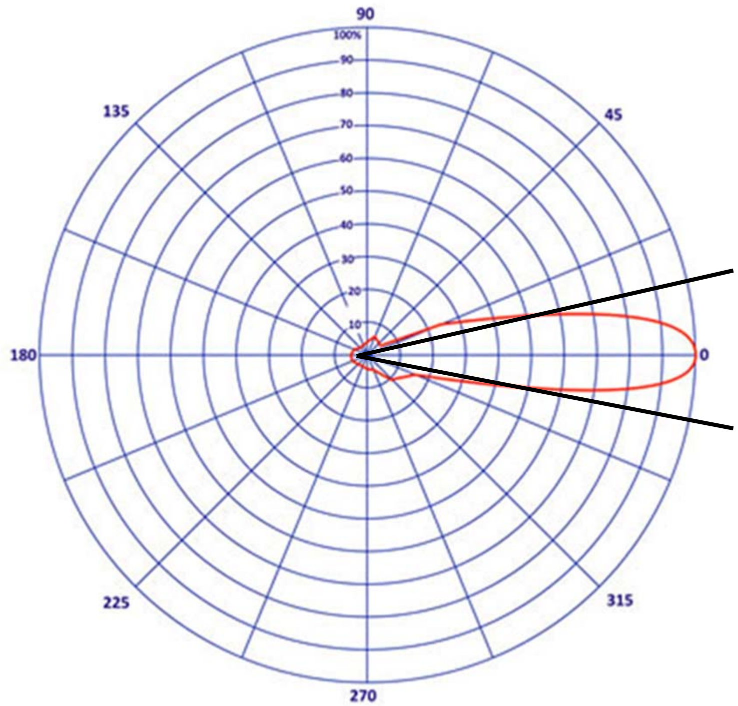


Rotated 90º CW

X-ray Beam Coverage

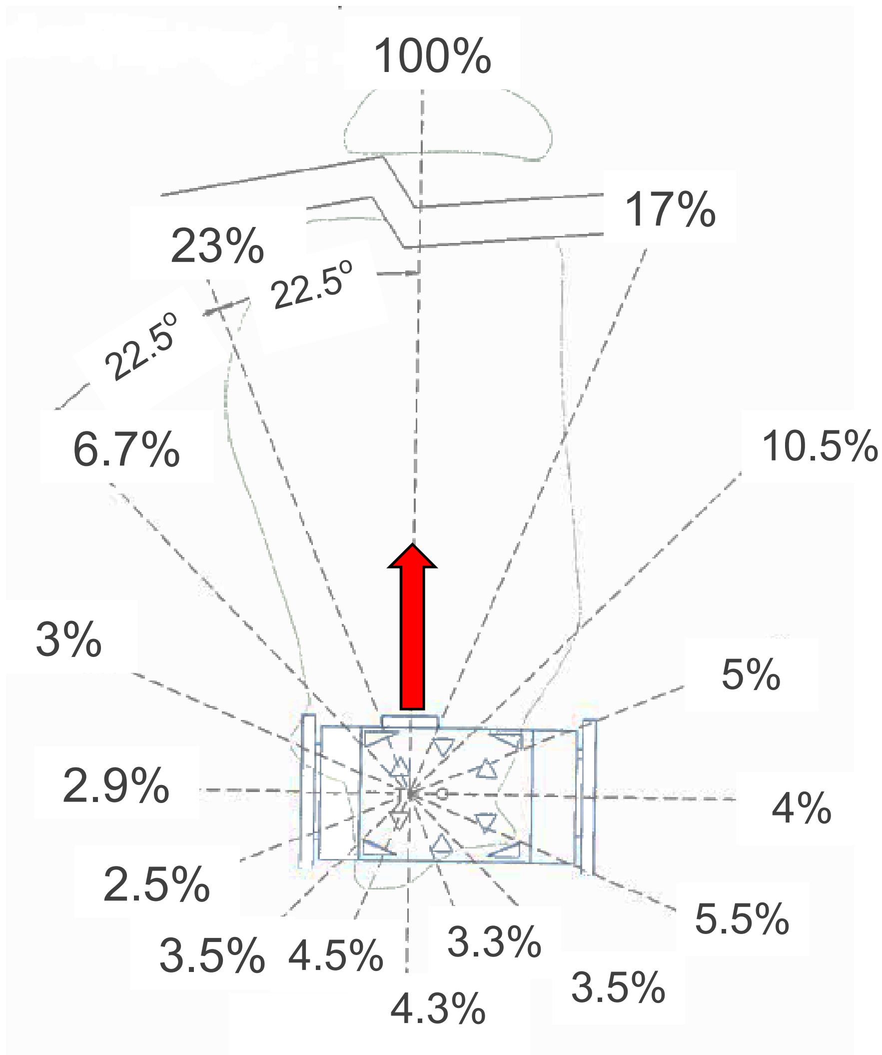
30 degree cone (100% to 50% intensity)

Distance	Beam Diameter	100% Intensity
1 m	0.54m	80 mGy/min
2 m	1.1m	20 mGy/mi
3 m	1.6m	9 mGy/mi
4 m	2.1m	5 mGy/mi
5 m	2.7m	3 mGy/mi
10 m	5.4m	0.8 mGy/mi

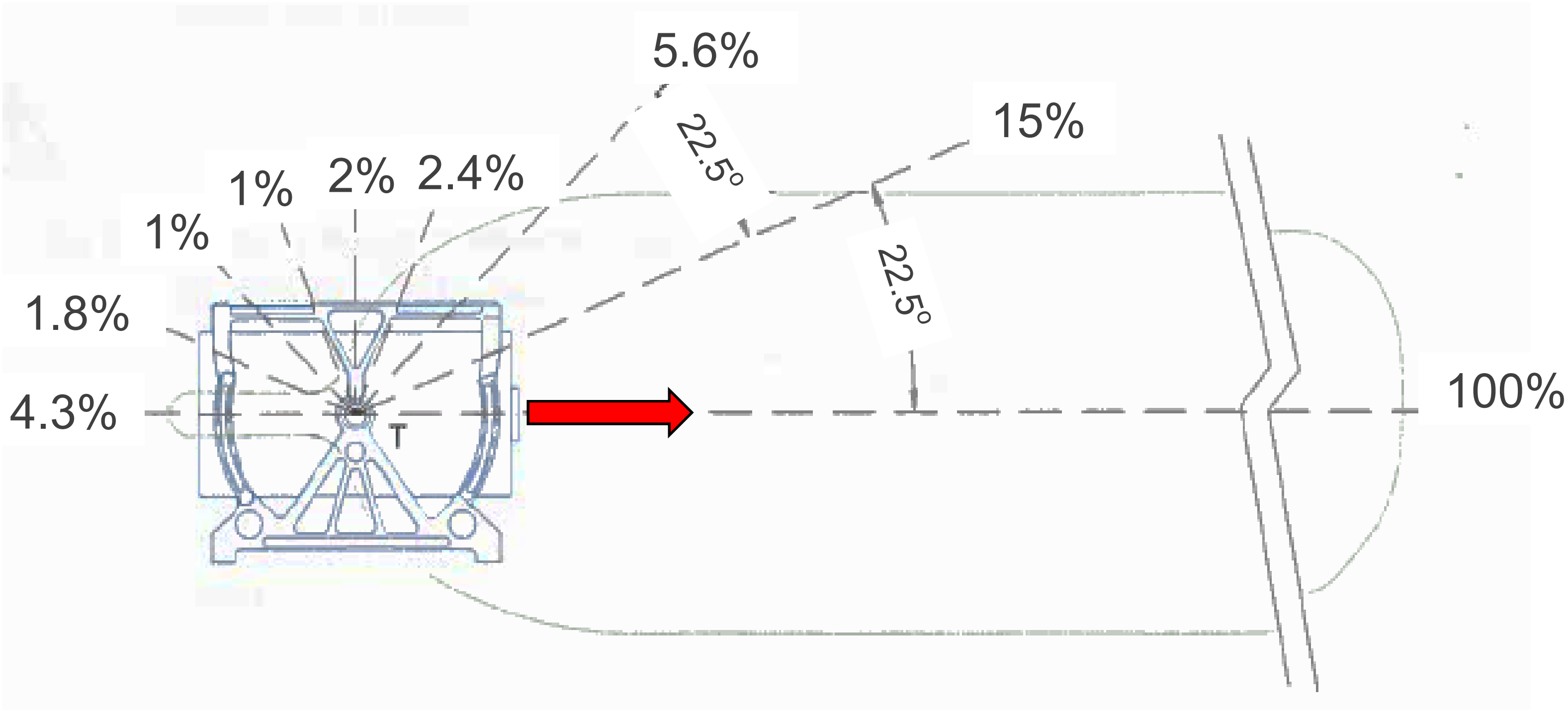


STABILIZATION PROGRAM
NNSA NA-42

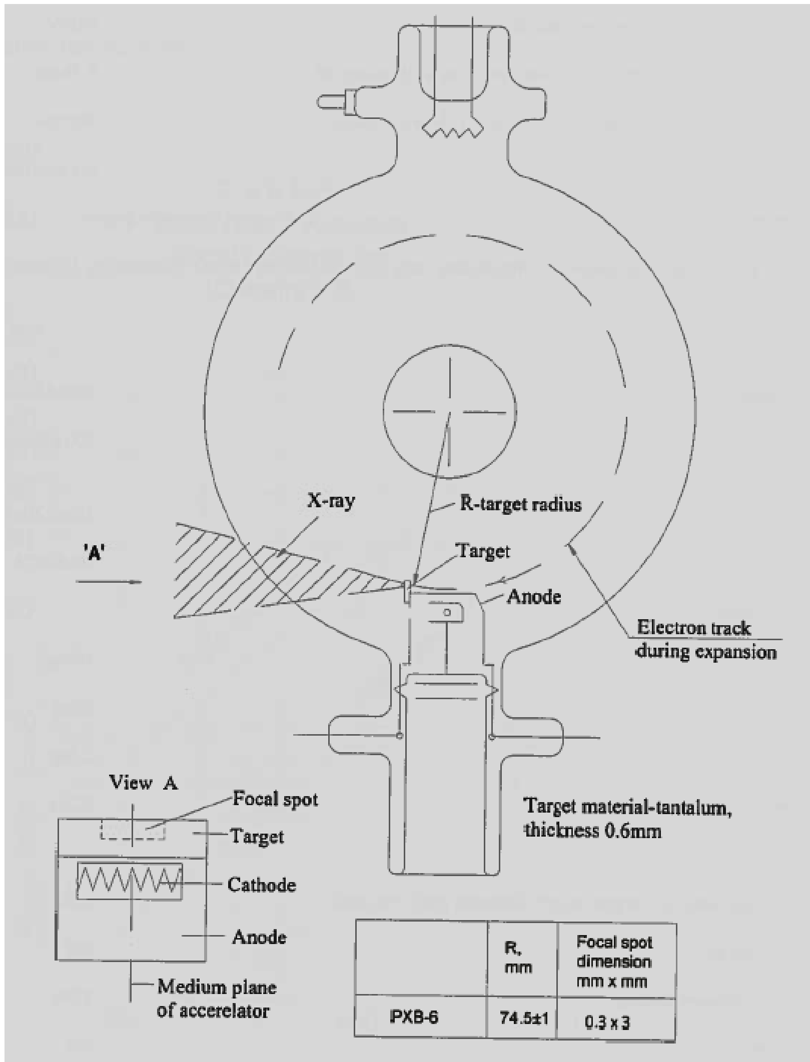
Betatron's Radiation Pattern



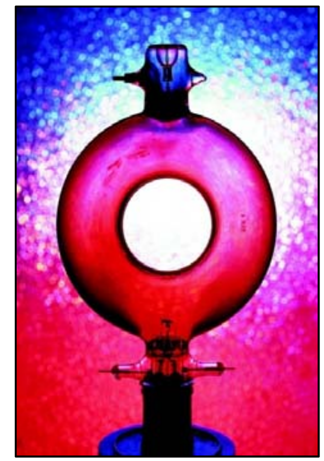
Betatron's Radiation Pattern
(cont'd)

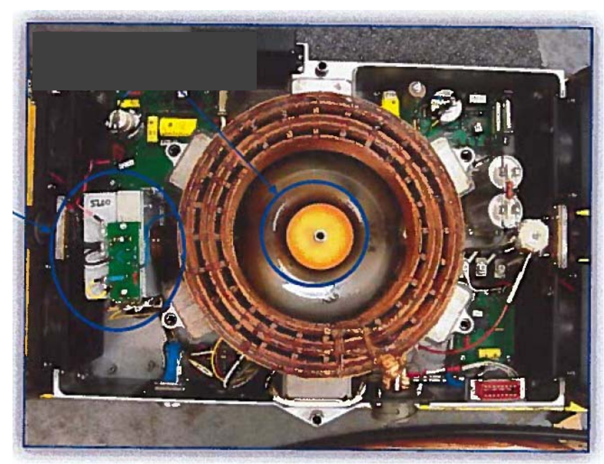


Focal Spot Location



	R, mm	Focal spot dimension mm x mm
PXB-6	74.5±1	0.3 x 3





Examples: 3m SID, 2.9m SOD

- **Betatron/ScanX**
  - M = 1.05
  - Ug = 50 µm
  - SRb = 200 µm (0.008”)
  - Ut = 403 µm (0.016”)

Examples: 3m SID, 2.4m SOD

- **Betatron/CR**
  - M = 1.25
  - Ug = 250 µm (0.010”)
  - SRb = 200 µm (0.008”)
  - Ut = 472 µm (0.019”)

Examples: 6m SID, 2.9m SOD

- **Betatron/CR**
  - M = 1.025
  - Ug = 25 µm (0.001”)
  - SRb = 200 µm (0.008”)
  - Ut = 401 µm (0.016”)

Exposure 4X longer than 3m for same PV and SNR

Examples: 6m SID, 5.5m SOD

- **Betatron/CR**
  - M = 1.11
  - Ug = 111 µm
  - SRb = 200 µm (0.008”)
  - Ut = 415 µm (0.016”)

Exposure 4X longer than 3m for same PV and SNR

Image Size

ScanX scanner – Standard scan

Pixel Size		36cm x 43cm	3x3 mosaic
168 um	2116x2570	11 MB	99 MB
134 um		17 MB	153 MB
50 um	7112x8636	123 MB	1.1 GB

Radiographic Technique

Parameters needed to define a radiography procedure:

- Distances (Source to Image, Object to Image)
- Energy/Filter
- Focal Spot
- Collimation
- Exposure (R/Gy or time)
- Scanner settings (resolution, gain)
- Signal Level/SNR
- Views: Rotation/Angle

Lesson Summary

- **Focal Spot Size**
  - Affects blur
- **Distance Focal Spot to Imager**
  - Affects blur
  - Affects exposure ($1/r^2$)
  - Affects field of view
- **Distance Object to Image**
  - Affects blur
  - Affects scatter
- **View Angle and Rotation**
  - Affects distortion/parallax
  - Affects overlap

Betatron Course

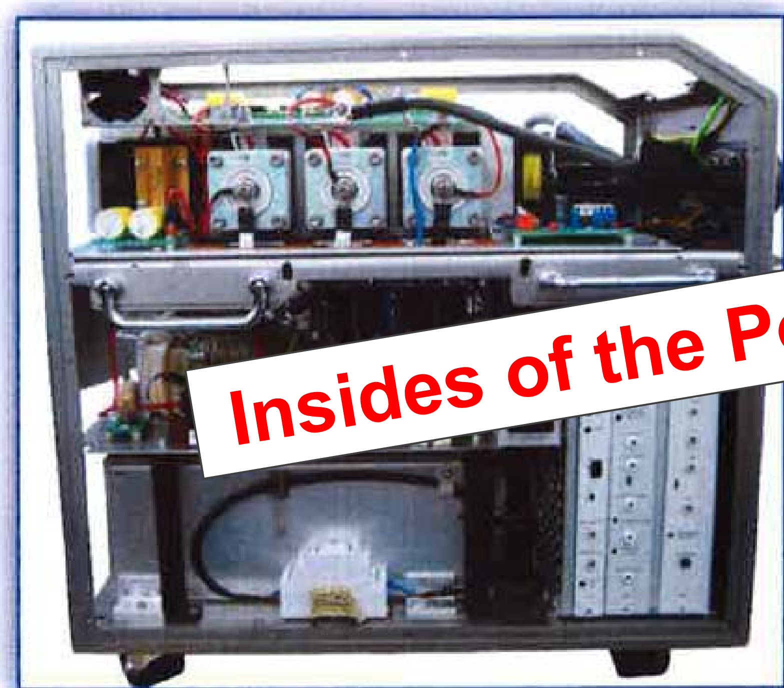
Lesson 7

Betatron Troubleshooting and Maintenance

Lesson Objectives

- Identify the **extra repair equipment** that comes with the Betatron system
- Explain **basic care procedures** for the Betatron system
- Identify **troubleshooting procedures for simple problems** that can arise with the Betatron system
- Identify the some **common error messages**, their cause, and possible solutions

DON’T Open Betatron Equipment



Two Manuals – Read Them!

Document Number: PXB6MJ/OP
Revision: 02
Date of Issue: 11/14

JME
ADVANCED INSPECTION SYSTEMS

Page 1 of 58

JME Portable 6 MeV X-Ray Betatron

Microprocessor model: PXB6MJ

Operators Manual

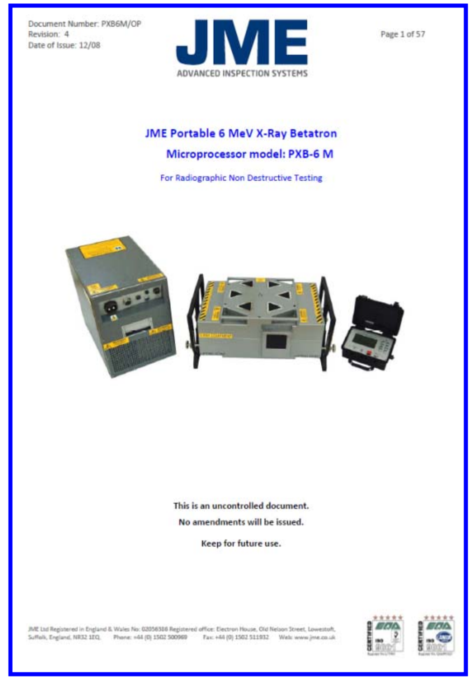
Original Instructions

This is an uncontrolled document.

No amendments will be issued.

Keep for future use.

Operator Manual



Document Number: PXB6M/OP
Revision: 4
Date of Issue: 12/08

JME
ADVANCED INSPECTION SYSTEMS

Page 1 of 57

JME Portable 6 MeV X-Ray Betatron

Microprocessor model: PXB-6 M

For Radiographic Non Destructive Testing

This is an uncontrolled document.

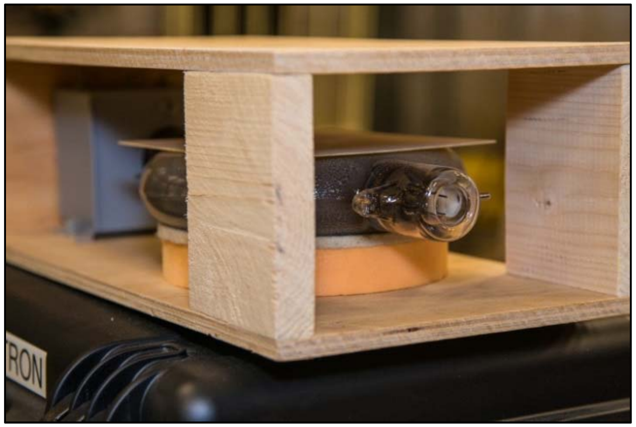
No amendments will be issued.

Keep for future use.

Maintenance Manual

Betatron Spares

Spares
Kit



Vacuum
Tube

Basic Care

Operating Environment

- **No condensing moisture or dust**
- **Run for 20 – 30 minutes (whenever possible)**
  - Blows out dust and moisture
- **Sufficient input power required**
  - Otherwise error messages
  - Generator should be at least 6 kV

Lifting

- Proper position of slings

X-ray Radiator

Power Unit

Cable Care

- Avoid sharp bends
- Avoid dropping – Ends can damage easily
- No cable spares with kit or at Stabilization facility in Albuquerque

HV cable

Basic Troubleshooting

Troubleshooting

Possible Symptoms

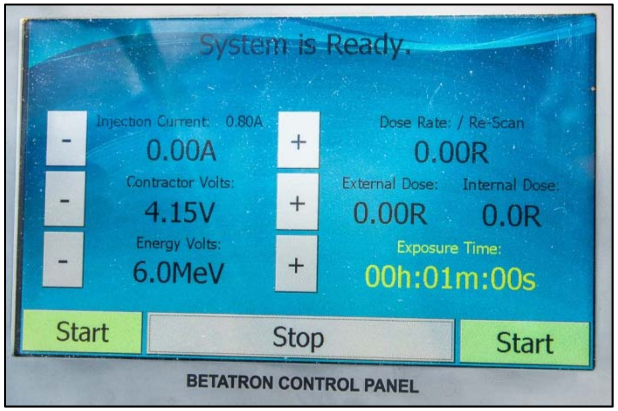
- Low radiation output
- No radiation output
- No magnet operation
- Error messages on Control Panel

Troubleshooting

Low Radiation Output

Control Panel

- Correct energy entered?
- Correct injection current set?
- Contractor voltage adjustment?
- Maximum dose rate selected?

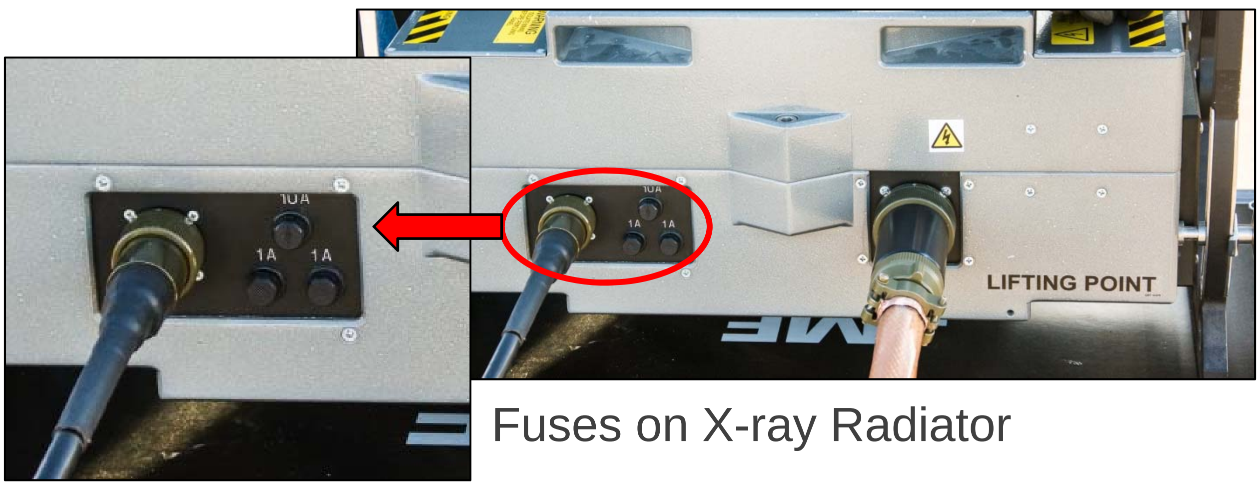


Troubleshooting

Low Radiation Output (cont'd)

X-ray Radiator

– Contractor fuse OK? If not, replace the fuse



Fuses on X-ray Radiator

Troubleshooting

Low Radiation Output (cont'd)

Power Unit

- Check injection and contractor voltage
- Voltage test points and adjustments on the Power Unit
- Refer to Maintenance Manual

Troubleshooting

No Radiation Output

X-ray Radiator

- All fuses OK? If not, replace them
- Is filament glowing? (check when powered up, but radiation off)
  - If no glow, most likely faulty tube
  - Also check filament voltage in Power Unit

Troubleshooting

No Radiation Output (cont'd)

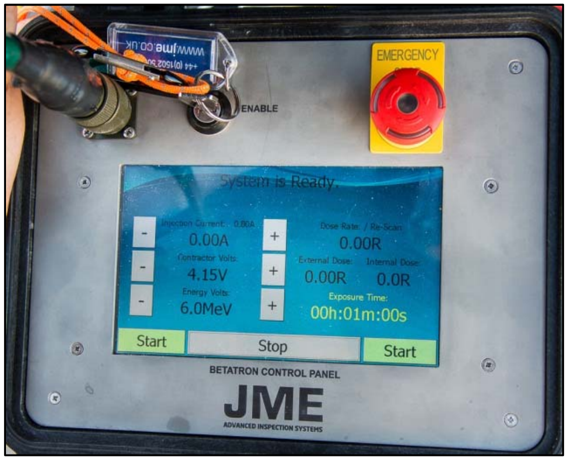
Power Unit

- All supply voltages OK?
- All trigger pulses present?
- Feedback normal?
- Refer to Maintenance Manual

Troubleshooting
No Magnet Operation

Control Panel

- Is Emergency Stop button pressed?
- Does system enter pre-warning phase after pressing START? If not, check interlocks?



Interlocks

Troubleshooting

No Magnet Operation (cont'd)

Power Unit

- Is circuit breaker switched on? If not, reset and try again.
- If breaker trips, possible fault with thyristor bridge in Power Unit or magnet coils in Radiator
- If breaker trips again, call your Stab Technician

Circuit breaker

Error Messages

Error Messages on Control Panel

"Waiting for Betatron to respond"

"Key Switch is Disabled"

"Delay time 10s"

"Door interlock is open"

"Over Current detected"

"Console power off"

"Overvoltage detected"

"Overheat-Radiator"

"Overheat-Diode" "Overheat-Thyristor"

"Faulty monitor"

"Low Filament"

"High Filament"

Error Messages

"Low filament"

- Indicates system cannot achieve the pre-set injection current
- What is injection current showing while running?
  - 0.00? No injection – Check fuses in head, and glow from tube
  - Lower than pre-set? Filament voltage requires adjustment

Error Messages (cont'd)

"High filament"

- Indicates system cannot achieve pre-set injection current – current is too high
- What is injection current showing while running?
  - Higher than pre-set? Filament voltage requires adjustment

Error Messages (cont'd)

"Current emergency"

- Indicates that system has shut down due to a high current being drawn by the magnet
- Cable damage?
- Water ingress?
- Faulty thyristors in Power Unit?

Error Messages (cont'd)

"Door interlock"

- Indicates that system has shut down due to an interlock being in an 'unsafe' condition
  - STOP button should clear message once interlocks are safe
- Check all connected interlocks
- Check lamp-fail indicator on A/V Warning Light

Other Issues

Radiation terminates early

- Check Control Panel settings
  - Is Automatic termination enabled?